(51) International Patent Classification 7 : H01S 5/323, H01L 33/00, 31/0304	A2	(11) International Publication Number: WO 00/59084
		(43) International Publication Date: 5 October 2000 (05.10.00)

(72) Inventors: TORU, Takayama; 2275 Sharon Road, No. 216, Menlo Park, CA 94015 (US). TAKAAKI, Baba; 535 Arboleda Drive, Los Altos, CA 94024 (US). HARRIS, James, S., Jr.; 763 Esplanada Way, Stanford, CA 94305 (US).

BEST AVAILABLE COPY

(54) Title: SEMICONDUCTORS STRUCTURES USING A GROUP III–NITRIDE QUATERNARY MATERIAL SYSTEM WITH REDUCED PHASE SEPARATION AND METHOD OF FABRICATION

(57) Abstract

A group III–nitride quaternary material system and method is disclosed for use in semiconductor structures, including laser diodes, transistors, and photodetectors, which reduces or eliminates phase separation and provides increased emission efficiency. In an exemplary embodiment the semiconductor structure includes a first InGaAlN layer of a first conduction type formed substantially without phase separation, an InGaAlN active layer substantially without phase separation, and a third InGaAlN layer of an opposite conduction type formed substantially without phase separation.

5

10

SEMICONDUCTORS STRUCTURES USING A GROUP III–NITRIDE QUATERNARY MATERIAL SYSTEM WITH REDUCED PHASE SEPARATION AND METHOD OF FABRICATION

15

20

SPECIFICATION

25

FIELD OF THE INVENTION

This application relates to semiconductor structures and processes, and particularly relates to group III-nitride materials systems and methods such as might 30 be used in blue laser diodes.

BACKGROUND OF THE INVENTION

The development of the blue laser light source has heralded the next 35 generation of high density optical devices, including disc memories, DVDs, and so on. Figure 1 shows a cross sectional illustration of a prior art semiconductor laser devices. (S. Nakamura, MRS BULLETIN, Vol. 23, No. 5, pp. 37-43, 1998.) On a

sapphire substrate 5, a gallium nitride (GaN) buffer layer 10 is formed, followed by an n-type GaN layer 15, and a 0.1 μm thick silicon dioxide (SiO_2) layer 20 which is patterned to form 4 μm wide stripe windows 25 with a periodicity of 12 μm in the GaN<1-100> direction. Thereafter, an n-type GaN layer 30, an n-type indium gallium

5   nitride ($In_{0.1}Ga_{0.9}N$) layer 35, an n-type aluminum gallium nitride ($Al_{0.14}Ga_{0.86}N$)/GaN MD-SLS (Modulation Doped Strained-Layer Superlattices) cladding layer 40, and an n-type GaN cladding layer 45 are formed. Next, an $In_{0.02}Ga_{0.98}N/In_{0.15}Ga_{0.85}N$ MQW (Multiple Quantum Well) active layer 50 is formed followed by a p-type $Al_{0.2}Ga_{0.8}N$ cladding layer 55, a p-type GaN cladding layer 60, a p-type $Al_{0.14}Ga_{0.86}N$/GaN MD-

10   SLS cladding layer 65, and a p-type GaN cladding layer 70. A ridge stripe structure is formed in the p-type $Al_{0.14}Ga_{0.86}N$/GaN MD-SLS cladding layer 55 to confine the optical field which propagates in the ridge waveguide structure in the lateral direction. Electrodes are formed on the p-type GaN cladding layer 70 and n-type GaN cladding layer 30 to provide current injection.

15   In the structure shown in Figure 1, the n-type GaN cladding layer 45 and the p-type GaN 60 cladding layer are light-guiding layers. The n-type $Al_{0.14}Ga_{0.86}N$/GaN MD-SLS cladding layer 40 and the p-type $Al_{0.14}Ga_{0.86}N$/GaN MD-SLS cladding layer 65 act as cladding layers for confinement of the carriers and the light emitted from the active region of the InGaN MQW layer 50. The n-type $In_{0.1}Ga_{0.9}N$ layer 35 serves

20   as a buffer layer for the thick AlGaN film growth to prevent cracking.

        By using the structure shown in Figure 1, carriers are injected into the InGaN MQW active layer 50 through the electrodes, leading to emission of light in the wavelength region of 400 nm. The optical field is confined in the active layer in the lateral direction due to the ridge waveguide structure formed in the p-type $Al_{0.1}$

25   $_4Ga_{0.86}N$/GaN MD-SLS cladding layer 65 because the effective refractive index under the ridge stripe region is larger than that outside the ridge stripe region. On the other hand, the optical field is confined in the active layer in the transverse direction by the n-type GaN cladding layer 45, the n-type $Al_{0.14}Ga_{0.86}N$/GaN MD-SLS cladding layers 40, the p-type GaN cladding layer 60, and the p-type $Al_{0.14}Ga_{0.86}N$/GaN MD-SLS

30   cladding layer 55 because the refractive index of the of the active layer is larger than that of the n-type GaN cladding layer 45 and the p-type GaN cladding layer 60, the n-type $Al_{0.14}Ga_{0.86}N$/GaN MD-SLS layer 40, and the p-type $Al_{0.14}Ga_{0.86}N$/GaN MD-SLS cladding layer 60. Therefore, fundamental transverse mode operation is obtained.

        However, for the structure shown in Figure 1, it is difficult to reduce the defect

35   density to the order of less than $10^8\,cm^{-2}$, because the lattice constants of AlGaN, InGaN, and GaN differ sufficiently different from each other that defects are generated in the structure as a way to release the strain energy whenever the total

thickness of the n-type $In_{0.1}Ga_{0.9}N$ layer 35, the $In_{0.02}Ga_{0.98}N/In_{0.15}Ga_{0.85}N$ MQW active layer 50, the n-type $Al_{0.14}Ga_{0.86}N/GaN$ MD-SLS cladding layer 40, the p-type $Al_{0.14}Ga_{0.86}N/GaN$ MD-SLS cladding layer 65, and the p-type $Al_{0.2}Ga_{0.8}N$ cladding layer 55 exceeds the critical thickness. The defects result from phase separation and act

5   as absorption centers for the lasing light, causing decreased light emission efficiency and increased threshold current. The result is that the operating current becomes large, which in turn causes reliability to suffer.

Moreover, the ternary alloy system of InGaN is used as an active layer in the structure shown in Figure 1. In this case, the band gap energy changes from 1.9 eV

10 for InN to 3.5 eV for GaN. Therefore, ultraviolet light which has an energy level higher than 3.5 eV cannot be obtained by using an InGaN active layer. This presents difficulties, since ultraviolet light is attractive as a light source for the optical pick up device in, for example, higher density optical disc memory systems and other devices.

15   To better understand the defects which result from phase separation in conventional ternary materials systems, the mismatch of lattice constants between InN, GaN, and AlN must be understood. The lattice mismatch between InN and GaN, between InN and AlN, and between GaN and AlN, are 11.3%, 13.9%, and 2.3%, respectively. Therefore, an internal strain energy accumulates in an InGaAlN

20 layer, even if the equivalent lattice constant is the same as that of the substrate due to the fact that equivalent bond lengths are different from each other between InN, GaN, and AlN. In order to reduce the internal strain energy, there is a compositional range which phase separates in the InGaAlN lattice mismatched material system, where In atoms, Ga atoms, and Al atoms are inhomogeneously distributed in the

25 layer. The result of phase separation is that In atoms, Ga atoms, and Al atoms in the InGaAlN layers are not distributed uniformly according to the atomic mole fraction in each constituent layer. In turn, this means the band gap energy distribution of any layer which includes phase separation also becomes inhomogeneous. The band gap region of the phase separated portion acts disproportionately as an optical

30 absorption center or causes optical scattering for the waveguided light. As noted above, a typical prior art solution to these problems has been to increase drive current, thus reducing the life of the semiconductor device.

As a result, there has been a long felt need for a semiconductor structure which minimizes lattice defects due to phase separation and can be used, for

35 example, as a laser diode which emits blue or UV light at high efficiency, and for other semiconductor structures such as transistors.

SUMMARY OF THE INVENTION

The present invention substantially overcomes the limitations of the prior art by providing a semiconductor structure which substantially reduces defect densities by materially reducing phase separation between the layers of the structure. This in turn permits substantially improved emission efficiency.

To reduce phase separation, it has been found possible to provide a semiconductor device with InGaAlN layers having homogeneous In content, Al content, Ga content distribution in each layer. In a light emitting device, this permits optical absorption loss and waveguide scattering loss to be reduced, resulting in a high efficiency light emitting device.

A quaternary material system such as InGaAlN has been found to provide, reproducibly, sufficient homogeneity to substantially reduce phase separation where the GaN mole fraction, x, and the AlN mole fraction, y, of all the constituent layers in the semiconductor structure satisfy the condition that $x + 1.2y$ nearly equals a constant value.

A device according to the present invention typically includes a first layer of InGaAlN material of a first conductivity, an InGaAlN active layer, and a layer of InGaAlN material of an opposite conductivity successively formed on one another. By maintaining the mole fractions essentially in accordance with the formula $x + 1.2y$ equals a constant, for example on the order of or nearly equal to one, the lattice constants of the constituent layers remain substantially equal to each other, leading to decreased generation of defects.

In an alternative embodiment, the semiconductor structure is fabricated essentially as above, using a quaternary materials system to eliminate phase separation and promote homogeneity across the layer boundaries. Thus, as before, the first cladding layer is a first conduction type and composition of InGaAlN, the active layer is InGaAlN of a second composition, and the second cladding layer is an opposite conduction type of InGaAlN having the composition of the first layer. However, in addition, the second cladding layer has a ridge structure. As before, the optical absorption loss and waveguide scattering loss is reduced, leading to higher efficiencies, with added benefit that the optical field is able to be confined in the lateral direction in the active layer under the ridge structure. This structure also permits fundamental transverse mode operation.

In a third embodiment of the invention, suited particularly to implementation as a laser diode, the semiconductor structure comprises a first cladding of a first conduction type of an $In_{1-x1-y1}Ga_{x1}Al_{y1}N$ material, an active layer of an $In_{1-x2-y2}Ga_{x2}Al_{y2}N$

material, and a second cladding layer of an opposite conduction type of an $In_{1-x3-y3}Ga_{x3}Al_{y3}N$ material, each successively formed on the prior layer. In such a materials system, x1, x2, and x3 define the GaN mole fraction and y1, y2, and y3 define the AlN mole fraction and x1, y1, x2, y2, x3, and y3 have a relationship of $0 < x1 + y1 < 1$,

5    $0 < x2 + y2 < 1$, $0 < x3 + y3 < 1$, $1 <= x1/0.80 + y1/0.89$, $1 <= x2/0.80 + y2/0.89$, $1 <= x3/0.80 + y3/0.89$, $Eg_{InN}(1-x1-y1) + Eg_{GaN}x1 + Eg_{AlN}y1 > Eg_{InN}(1-x2-y2) + Eg_{GaN}x2 + Eg_{AlN}y2$, and $Eg_{InN}(1-x3-y3) + Eg_{GaN}x3 + Eg_{AlN}y3 > Eg_{InN}(1-x2-y2) + Eg_{GaN}x2 + Eg_{AlN}y2$, where Eg_{InN}, Eg_{GaN}, and Eg_{AlN} are the band gap energy of InN, GaN, and AlN, respectively.

10   To provide a reproducible semiconductor structure according to the above materials system, an exemplary embodiment of InGaAlN layers have Ga content, x, and Al content, y, which satisfy the relationship $0 < x + y < 1$ and $1 <= x/0.80 + y/0.89$. As before, this materials system permits reduction of the optical absorption loss and the waveguide scattering loss, resulting in a high efficiency light emitting device.

15 Moreover, the band gap energy of the InGaAlN of an active layer becomes smaller than that of the first cladding layer and the second cladding layer when x1, y1, x2, y2, x3, and y3 have a relationship of $0 < x1 + y1 < 1$, $0 < x2 + y2 < 1$, $0 < x3 + y3 < 1$, $1 <= x1/0.80 + y1/0.89$, $1 <= x2/0.80 + y2/0.89$, $1 <= x3/0.80 + y3/0.89$, $Eg_{InN}(1-x1-y1) + Eg_{GaN}x1 + Eg_{AlN}y1 > Eg_{InN}(1-x2-y2) + Eg_{GaN}x2 + Eg_{AlN}y2$, and $Eg_{InN}(1-x3-y3) +$

20 $Eg_{GaN}x3 + Eg_{AlN}y3 > Eg_{InN}(1-x2-y2) + Eg_{GaN}x2 + Eg_{AlN}y2$. Under these conditions, the injected carriers are confined in the active layer. In at least some embodiments, it is preferable that the third light emitting device has an InGaAlN single or multiple quantum well active layer whose GaN mole fraction, xw, and AlN mole fraction, yw, of all the constituent layers satisfy the relationship of $0 < xw + yw < 1$ and $1 <= x/0.80$

25 $+ y/0.89$.

        One of the benefits of the foregoing structure is to reduce the threshold current density of a laser diode. This can be achieved by use of a single or multiple quantum well structure, which reduces the density of the states of the active layer. This causes the carrier density necessary for population inversion to become smaller,

30 leading to a reduced or low threshold current density laser diode.

        It is preferred that in the third light emitting device, the condition of $xs + 1.2ys$ nearly equals to a constant value -- on the order of or near one -- is satisfied, wherein xs and ys are the GaN mole fraction and the AlN mole fraction, respectively in each the constituent layers. As before, this causes the lattice constants of the each

35 constituent layers to be nearly equal to each other, which in turn substantially minimizes defects due to phase separation

        In a fourth embodiment of the present invention, the semiconductor structure

may comprise a first cladding layer of a first conduction type of a material $In_{1-x1-y1}Ga_{x1}Al_{y1}N$, an $In_{1-x2-y2}Ga_{x2}Al_{y2}N$ active layer, and a second cladding layer of an opposite conduction type of a material $In_{1-x3-y3}Ga_{x3}Al_{y3}N$, each successively formed one upon the prior layer. In addition, the second cladding layer has a ridge structure.

5   For the foregoing materials system, x1, x2, and x3 define the GaN mole fraction, y1, y2, and y3 define the AlN mole fraction, and x1, y1, x2, y2, x3, and y3 have a relationship of $0 < x1 + y1 < 1$, $0 < x2 + y2 < 1$, $0 < x3 + y3 < 1$, $1 <= x1/0.80 + y1/0.89$, $1 <= x2/0.80 + y2/0.89$, $1 <= x3/0.80 + y3/0.89$, $Eg_{InN}(1-x1-y1) + Eg_{GaN}x1 + Eg_{AlN}y1 > Eg_{InN}(1-x2-y2) + Eg_{GaN}x2 + Eg_{AlN}y2$, and $Eg_{InN}(1-x3-y3) + Eg_{GaN}x3 + Eg_{AlN}y3 > Eg_{InN}(1-x2-y2) + Eg_{GaN}x2 + Eg_{AlN}y2$, where Eg_{InN}, Eg_{GaN}, and Eg_{AlN} are the bandgap energy of InN, GaN, and AlN, respectively.

As with the prior embodiments, each of the InGaAlN layers have a homogeneous In content, Al content, and Ga content distribution, which can be obtained reproducibly when Ga content, x, Al content, y, of each InGaAlN layer

15 satisfies the relationship $0 < x + y < 1$ and $1 <= x/0.80 + y/0.89$. The band gap energy of the InGaAlN active layer becomes smaller than that of the first cladding layer and the second cladding layer when x1, y1, x2, y2, x3, and y3 have a relationship of $0 < x1 + y1 < 1$, $0 < x2 + y2 < 1$, $0 < x3 + y3 < 1$, $1 <= x1/0.80 + y1/0.89$, $1 <= x2/0.80 + y2/0.89$, $1 <= x3/0.80 + y3/0.89$, $Eg_{InN}(1-x1-y1) + Eg_{GaN}x1 + Eg_{AlN}y1 > Eg_{InN}(1-x2-y2)$

20 $+ Eg_{GaN}x2 + Eg_{AlN}y2$, and $Eg_{InN}(1-x3-y3) + Eg_{GaN}x3 + Eg_{AlN}y3 > Eg_{InN}(1-x2-y2) + Eg_{GaN}x2 + Eg_{AlN}y2$. Similar to the prior embodiments, the injected carriers are confined in the active layer and the optical field is confined in the lateral direction in the active layer under the ridge structure, producing a fundamental transverse mode operation.

25 Also similar to the prior embodiments, the fourth embodiment typically includes an InGaAlN single or multiple quantum well active layer whose GaN mole fraction, xw, and AlN mole fraction, yw of all the constituent layers satisfy the relationship of $0 < xw + yw < 1$ and $1 <= x/0.80 + y/0.89$. Also, the condition xs + 1.2ys nearly equals to a constant value on the order of or near one is typically

30 satisfied, where xs and ys are the GaN mole fraction and the AlN mole fraction, respectively in each constituent layer. Similar parameters apply for other substrates, such as sapphire, silicon carbide, and so on.

The foregoing results may be achieved with conventional processing temperatures and times, typically in the range of 500°C to 1000°C. See "Growth of

35 high optical and electrical quality GaN layers using low-pressure metalorganic chemical vapor deposition," *Appl. Phys. Lett. 58 (5)*, 4 February 1991 p. 526 et seq.

The present invention may be better appreciated by the following Detailed

Description of the Invention, taken together with the attached Figures.

FIGURES

Figure 1 shows a prior art laser diode structure using a conventional ternary
5 materials system.

Figure 2 shows in cross-sectional view a semiconductor structure according
to a first embodiment of the invention.

Figure 3 shows a graph of the light-current characteristics of a laser diode
according to the structure of Figure 1.

10 Figure 4 shows an exemplary series of the fabrication steps for a
semiconductor structure in accordance with a first embodiment of the invention.

Figure 5 shows in cross-sectional view a semiconductor structure according
to a second embodiment.

Figure 6 shows a graph of the light-current characteristics of a laser diode
15 according to the structure of Figure 4.

Figure 7 shows an exemplary series of the fabrication steps for a
semiconductor structure in accordance with the first embodiment of the invention.

Figure 8 is a cross-sectional illustration of a semiconductor laser diode of the
third embodiment.

20 Figure 9 shows the light-current characteristics of the laser diode of the third
embodiment.

Figure 10 shows a series of the fabrication steps of a semiconductor laser
diode in one experiment example of the third embodiment.

Figure 11 is a cross-sectional illustration of a semiconductor laser diode of the
25 fourth embodiment.

Figure 12 shows the light-current characteristics of the laser diode of the
fourth embodiment.

Figure 13 shows a series of the fabrication steps of a semiconductor laser
diode in one experiment example of the fourth embodiment.

30 Figure 14 shows in plot form the boundary between the phase separation
region and the region without phase separation at various growth temperatures.

Figure 15 shows the content choice region of Ga content and Al content in
InGaAlN to avoid phase separation at a growth temperature below approximately
1000 °C.

35 Figure 16 shows the content choice line of Ga content and Al content in
InGaAlN to avoid phase separation at a growth temperature below approximately
1000 °C which, at the same time, creates a lattice constant of InGaAlN substantially

equivalent to that of GaN.

Figures 17A and 17B show representations of bipolar and FET transistors constructed in accordance with the materials system of the present invention.

Figure 18 shows an implementation of the presention invention as a
5 phototransistor.

Figure 19 shows an implementation of the present invention as a photodiode.

DETAILED DESCRIPTION OF THE INVENTION

10   Referring first to Figure 2, shown therein in cross-sectional view is a semiconductor structure according to a first embodiment of the invention.   For purposes of illustration, the semicoductor structure shown in many of the Figures will be a laser diode, although the present invention has appliction to a number of device types.   A diode of the first embodiment. With particular reference to Figure 1, an
15 n-type GaN substrate 100 is provided and an n-type GaN first cladding layer 105 (typically 0.5μm thick) is formed thereon. Thereafter, a second cladding layer 110, typically of an n-type $In_{0.05}Ga_{0.75}Al_{0.2}N$ material which may be on the order of 1.5 μm thick, is formed thereon, followed by a multiple quantum well active layer 115 which in an exemplary arrangement may comprise three quantum well layers of
20 $In_{0.01}Ga_{0.96}Al_{0.03}N$ material on the order of 35Å thick together with four barrier layers of $In_{0.02}Ga_{0.85}Al_{0.13}N$ material on the order of 35Å thick, arranged as three pairs. Next, a third cladding layer 120 of a p-type $In_{0.05}Ga_{0.75}Al_{0.2}N$(typically on the order of 1.5 mm thick) is formed, followed by a p-type GaN fifth cladding layer 125 (on the order of 0.5μm thick). A SiO_2 layer 130 having one stripe like window region 135 (3.0μm
25 width) is formed on the p-type GaN fourth cladding layer 125. A first electrode 140 is formed on the n-type GaN substrate 100, while a second electrode 145 is formed on the SiO_2 layer 130 and the window region 135. .

In order to emit ultra violet light with a wavelength range of 350 nm from the active layer 115, the InN mole fraction, the GaN mole fraction, and the AlN mole
30 fraction of the well layer are set to be 0.01, 0.96, and 0.03, respectively. To avoid defects due to phase separation, the lattice constants of the various constituent layers are matched to each other by setting the GaN mole fraction, x, and the AlN, y, in each of the layers to meet the condition x + 1.2y nearly equals a constant value. In an exemplary embodiment, the constant value is set to nearly one, for example
35 1 ± 0.1, although most embodiments will be in the range 1 ± 0.05.

By proper selection of materials, the band gap energy of the n-type second cladding layer 110 and the p-type third cladding layer 120 are larger than that of the

3 pairs of multiple quantum well active layers 115. This confines the injected carriers from the n-type second cladding layer 110 and p-type third cladding layer 120 within the active layer 115, where the carriers recombine to lead to the emission of ultraviolet light. In addition, the refractive index of the n-type second cladding layer

5 110 and the p-type third cladding layer 120 are smaller than that of the multiple quantum well active layer 115, which confines the optical field in the transverse direction.

Because the injected current from the electrode 145 is confined to flow through the window region 135, the region in the active layer 115 under the widow

10 region 135 is activated strongly. This causes the local modal gain in the active layer under the window region 6a to be higher than the local modal gain in the active layer under the SiO$_2$ layer. Therefore, a gain guided waveguide mechanism, leading to a lasing oscillation, is able to be formed in the structure of the first embodiment.

Figure 3 shows a plot of the emitted light versus drive current for a laser diode

15 constructed in accordance with the first embodiment. The laser diode is driven with a pulsed current with a duty cycle of 1 %. The threshold current density is found to be 5.5 kA/cm^2.

Figures 4A-4D show, in sequence, a summary of the fabrication steps necessary to construct an exemplary laser diode according to the first embodiment.

20 Since the structure which results from Figures 4A-4D will resemble that shown in Figure 2, like reference numerals will be used for elements whenever possible. With reference first to Figure 4A, an n-type GaN substrate 100 is provided, on which is grown an n-type GaN first cladding layer 105. The first cladding layer 105 is typically on the order of 0.5μm thick. Thereafter, an n-type $In_{0.05}Ga_{0.75}Al_{0.2}N$ second cladding

25 layer 110 is formed, typically on the order of 1.5 μm thick.

Next, a multiple quantum well active layer 115 is formed by creating three quantum wells comprised of three layers of $In_{0.01}Ga_{0.96}Al_{0.03}N$ material each on the order of 35Å thick, together with four barrier layers of $In_{0.02}Ga_{0.85}Al_{0.13}N$ material on the order of 35Å thick. A third cladding layer 120 of p-type $In_{0.05}Ga_{0.75}Al_{0.2}N$ material,

30 on the order of 1.5 μm thick, is then formed, after which is formed a fourth cladding layer 125 of a p-type GaN on the order of 0.5μm thick. Each of the layers is typically formed by either the Metal Organic Chemical Vapor Deposition (MOCVD) method or the Molecular Beam Epitaxy (MBE) method.

Then, as shown in Figure 4B, a silicon dioxide (SiO$_2$) layer 130 is formed on

35 the p-type GaN fourth cladding layer 125, for example by the Chemical Vapor Deposition (CVD) method. Using photolithography and etching or any other suitable method, a window region 135 is formed as shown in Figure 4C. The window region

135 may be stripe-like in at least some embodiments. Finally, as shown in Figure 4D, a first electrode 140 and a second electrode 145 are formed on the n-type GaN substrate 100 and on the SiO$_2$ layer 130, respectively, by evaporation or any other suitable process.

5   Referring next to Figure 5, a second embodiment of a semiconductor structure in accordance with the present invention may be better appreciated. As with the first embodiment, an exemplary application of the second embodiment is the creation of a laser diode. The structure of the second embodiment permits a waveguide mechanism to be built into the structure with a real refractive index guide. This

10 provides a low threshold current laser diode which can operate with a fundamental transverse mode.

          Continuing with reference to Figure 5, for ease of reference, like elements will be indicated with like reference numerals. On an n-type GaN substrate 100, a first cladding layer 105 is formed of an n-type GaN on the order of 0.5μm thick.

15 Successively, an n-type second cladding layer 110 is formed of In$_{0.05}$Ga$_{0.75}$Al$_{0.2}$N material on the order of 1.5 μm thick. Thereafter, a multiple quantum well active layer 115 is formed comprising three well layers of In$_{0.01}$Ga$_{0.96}$Al$_{0.03}$N material on the order of 35Å thick together with four barrier layers of In$_{0.02}$Ga$_{0.85}$Al$_{0.13}$N material, also on the order of 35Å thick. Next, a third, p-type cladding layer 120 formed of

20 In$_{0.05}$Ga$_{0.75}$Al$_{0.2}$N material on the order of 1.5 μm thick is formed. Thereafter, a p-type GaN fourth cladding layer 125 on the order of 0.5μm thick is formed over the ridge structure 500 of the third cladding layer 120. The third and fourth cladding layers are then partially removed to create a ridge structure 500. A silicon dioxide (SiO$_2$) layer 130 is then formed over over the fourth cladding layer 125 as well as the remaining

25 exposed portion of the third cladding layer 120. A window region 135, which may be stripe-like on the order of 2.0μm width, is formed through the SiO$_2$ layer above the fourth and third cladding layers 125 and 120, respectively. As with the first embodiment, a first electrode 140 is formed on the n-type GaN substrate 100 and a second electrode 145 is formed on the SiO$_2$ layer 130 and the window region 135.

30   As with the first embodiment, in order to emit ultra violet light with a wavelength in the range of 350 nm from the active layer 14, the mole fractions of InN, GaN, and AlN in the well layer are set to be 0.01, 0.96, and 0.03, respectively. Likewise, in order to match the lattice constants of each of the constituent layers to avoid defects due to phase separation, the GaN mole fraction, x, and the AlN, y, of

35 all the layers satisfy the condition of x + 1.2y nearly equals a constant value. As in the first embodiment, x + 1.2y set to be nearly equals 1 so that the equivalent lattice constants of each layers become nearly equal to the lattice constant of GaN.

135 may be stripe-like in at least some embodiments. Finally, as shown in Figure 4D, a first electrode 140 and a second electrode 145 are formed on the n-type GaN substrate 100 and on the SiO$_2$ layer 130, respectively, by evaporation or any other suitable process.

5   Referring next to Figure 5, a second embodiment of a semiconductor structure in accordance with the present invention may be better appreciated. As with the first embodiment, an exemplary application of the second embodiment is the creation of a laser diode. The structure of the second embodiment permits a waveguide mechanism to be built into the structure with a real refractive index guide. This

10   provides a low threshold current laser diode which can operate with a fundamental transverse mode.

          Continuing with reference to Figure 5, for ease of reference, like elements will be indicated with like reference numerals. On an n-type GaN substrate 100, a first cladding layer 105 is formed of an n-type GaN on the order of 0.5µm thick.

15   Successively, an n-type second cladding layer 110 is formed of In$_{0.05}$Ga$_{0.75}$Al$_{0.2}$N material on the order of 1.5 μm thick. Thereafter, a multiple quantum well active layer 115 is formed comprising three well layers of In$_{0.01}$Ga$_{0.96}$Al$_{0.03}$N material on the order of 35Å thick together with four barrier layers of In$_{0.02}$Ga$_{0.85}$Al$_{0.13}$N material, also on the order of 35Å thick. Next, a third, p-type cladding layer 120 formed of

20   In$_{0.05}$Ga$_{0.75}$Al$_{0.2}$N material on the order of 1.5 μm thick is formed. Thereafter, a p-type GaN fourth cladding layer 125 on the order of 0.5µm thick is formed over the ridge structure 500 of the third cladding layer 120. The third and fourth cladding layers are then partially removed to create a ridge structure 500. A silicon dioxide (SiO$_2$) layer 130 is then formed over over the fourth cladding layer 125 as well as the remaining

25   exposed portion of the third cladding layer 120. A window region 135, which may be stripe-like on the order of 2.0µm width, is formed through the SiO$_2$ layer above the fourth and third cladding layers 125 and 120, respectively. As with the first embodiment, a first electrode 140 is formed on the n-type GaN substrate 100 and a second electrode 145 is formed on the SiO$_2$ layer 130 and the window region 135.

30   As with the first embodiment, in order to emit ultra violet light with a wavelength in the range of 350 nm from the active layer 14, the mole fractions of InN, GaN, and AlN in the well layer are set to be 0.01, 0.96, and 0.03, respectively. Likewise, in order to match the lattice constants of each of the constituent layers to avoid defects due to phase separation, the GaN mole fraction, x, and the AlN, y, of

35   all the layers satisfy the condition of x + 1.2y nearly equals a constant value. As in the first embodiment, x + 1.2y set to be nearly equals 1 so that the equivalent lattice constants of each layers become nearly equal to the lattice constant of GaN.

Likewise, the band gap energy of the cladding layers is maintained larger than the band gap energy for the active layer, allowing the emission of ultraviolet light. Similarly the refractive index of the materials is as discussed in connection with the first embodiment, permitting the optical field to be confined in the transverse
5　direction.

Similar to the operation of the first embodiment, the region of the active layer 115 under the window region 135 is activated strongly because of the constraints on the injected current by the SiO2 layer. The result, again, is that the local modal gain in the active layer under the window region 135 is higher than the local modal gain
10　in the active layer under the SiO$_2$ layer 130. This, combined with the relatively higher effective refractive index in the transverse direction inside the ridge stripe region compared to that outside the ridge stripe region, provides an effective refractive index step (Dn). This results in a structure which has, built in, a waveguide mechanism of a real refractive index guide. Therefore, the design of the second
15　embodiment provides a low threshold current laser diode which can operate with a fundamental transverse mode.

Figure 6 shows in graph form the emitted light versus drive current characteristics of a laser diode in accordance with the second embodiment. The laser diode is driven with a cw current. The threshold current is found to be 32.5 mA.
20　　Referring next to Figures 7A-7E, a summary of the key fabrication steps is shown for an exemplary device of a semiconductor laser diode in accordance with the second embodiment.

Referring first to Figure 7A and 7B, the formation of the first and second cladding layers 105 and 110 on an n-type GaN substrate 100, together with the
25　three-pair multiple quantum well active layer 115 are the same as for the first embodiment. Thereafter, the third and fourth cladding layers 120 and 125 are formed and then partially removed -- typically by etching -- to create a ridge structure 500. As before, in an exemplary embodiment the various layers are formed successively by either the MOCVD or the MBE method.
30　　Then, as shown in Figure 7C-7E, a silicon dioxide layer 130 is formed over the fifth and third cladding layers 125 and 120, respectively, typically by the CVD method, after which a window region 135 is formed as with the first embodiment. Electrodes 140 and 145 are then evaporated or otherwise bonded to the structure.

Referring next to Figure 8, a third embodiment of the present invention may
35　be better appreciated. The third embodiment provides slightly different mole fractions to permit the emission of blue light, but is otherwise similar to the first embodiment. Thus, an n-type GaN substrate 100 continues to be used, together

with an n-type GaN first cladding layer 105. However, the second cladding layer 810 is typically of n-type $In_{0.15}Ga_{0.70}Al_{0.15}N$ material on the order of 1.5 μm thick, while the three-pair quantum well active layer 815 typically includes three barrier layers of $In_{0.15}Ga_{0.84}Al_{0.01}N$ material together with four barrier layers of $In_{0.16}Ga_{0.80}Al_{0.04}N$

5   material. The third cladding layer 820 is typically a p-type $In_{0.15}Ga_{0.70}Al_{0.15}N$ material, while the fourth cladding layer 125 is, like the first embodiment, a p-type GaN material. The thicknesses of each layer are substantially the same as for the first embodiment. A SiO_2 layer 130, window region 135, and first and second electrodes 140 and 145 complete the structure.

10   In order to emit blue light in a wavelength range of 400 nm from the active layer 24, the mole fractions of InN, GaN, and AlN within the well layer 815 are set to be 0.15, 0.84, and 0.15, respectively. In order to match the lattice constants of the constituent layers to avoid generation of phase separation-induced defects, the GaN mole fraction, x, and the AlN mole fraction, y, of each of the layers is set to satisfy the

15 condition x + 1.2y nearly equals a constant value on the order of 0.85 ± 0.1; as before, most embodiments will be in the range 0.85 ± 0.05.

       Although the third embodiment emits blue light whereas the first embodiment emits ultraviolet light, the band gap energies of cladding layers continue to be set higher than the band gap energy of the three pairs of the multiple quantum well

20 active layer 815. As before, the permits carrier confinement and recombination in the active layer 815. Also as with the first embodiment, the refractive index of the second and third cladding layers is, by design, smaller than that of the active layer, causing the optical field to be confined in the transverse direction. Likewise, the strong current injection under the window region 135 yields comparatively higher

25 local modal gain in the active layer relative to the portion of the active layer under the SiO2 layer 130, again resulting in a guided waveguide mechanism which leads to a lasing oscillation.

       Figure 9 shows a plot of the emitted light versus drive current characteristics of the laser diode in accordance with the third embodiment. The laser diode is driven

30 with a pulsed current with a duty cycle of 1 %. The threshold current density is found to be 5.0 kA/cm^2.

       Figures 10A-10D show a series of the fabrication steps of a semiconductor laser diode in one example of the third embodiment. It will be appreciated that the fabrication steps are the same as those described in connection with Figures 4A-4D,

35 and therefore are not further described.

       Referring next to Figure 11, a fourth embodiment of the present invention may be better appreciated. The fourth embodiment, like the third embodiment, is

designed to emit blue light and therefore has the same mole fractions as the third embodiment. However, like the second embodiment, the fourth embodiment is configured to provide a ridge structure to serve as a waveguide. Because the mole fractions are similar to those of Figure 8, similar elements will be described with the

5 reference numerals used in Figure 8.

Continuing to refer to Figure 11, the structure of the fourth embodiment can be seen to have a GaN substrate 100 on which is a formed a first cladding layer 105 followed by a second cladding layer 810. A three-pair multiple quantum well active layer 815 is formed thereabove, followed by a third cladding layer 820. A fourth

10 cladding layer 125, silicon dioxide layer 130, windows 135 and electrodes 140 and 145 are all formed as before. The materials, including the mole fractions of InN, GaN, and AlN, remain as shown for Figure 8, or 0.15, 0.84, and 0.01, respectively. Likewise the GaN mole fraction, x, and the AlN mole fraction, y, of the layers is set to satisfy the condition $x + 1.2y$ is equal to or nearly equal to a constant value on the

15 order of 0.85 ± 0.1, as with the prior embodiments. The band gap energy, refractive index and modal gain for current injection are all substantially as discussed in connection with the third embodiment and are not further discussed.

Figure 12 plots drive current versus emitted light of a laser diode constructed in accordance with the fourth embodiment. The laser diode is driven with a cw

20 current. The threshold current is found to be 28.5 mA.

Figure 13 shows a summary of the fabrication steps of a semiconductor laser diode in accordance with the fourth embodiment. The steps are essentially identical to those discussed in connection with Figures 7A-7E and are not further discussed.

Referring next to Figure 14, the selection of the GaN mole fraction, x, and the

25 AlN mole fraction, y, and the relationship therebetween for the constituent InGaAlN layers, may be better understood. In particular, the relative mole fractions are required to satisfy, approximately, the relationship $0 < x + y < 1$, $1 <= x/0.80 + y/0.89$.

Figure 14 shows the boundary of phase separation region plotted against various growth temperatures. The lines in Figure 14 show the boundary between the

30 compositionally unstable (phase separation) region and stable region with respect to various temperatures. The region surrounded with the InN-AlN line and the boundary line shows the phase separation content region. It has been discovered that the ternary alloys InAlN and InGaN have a large phase separation region due to the large lattice mismatch between InN and AlN, and between InN and GaN. On

35 the other hand, it is found that the ternary alloy GaAlN has no phase separation region for crystal growth at temperatures around 1000 °C, due to the small lattice mismatch between AlN and GaN.

It has therefore been discovered that an InGaAlN material system can be provided in which the usual crystal growth temperature is in the approximate range of around 500 °C to around 1000 °C. Likewise, it has been discovered that phase separation of the In content, Ga content, and Al content of InGaAlN does not occur

5   significantly at processing temperatures between on the order of 500 °C and on the order of 1000 °C. Finally, by combining the two, the content choice region of Ga content and Al content in InGaAlN to avoid phase separation at a crystal growth temperature below around 1000 °C is found to be the shadow region in Figure 15, with the line separating the two regions being approximately defined by the

10 relationship $x/0.80 + y/0.89 = 1$.

Therefore, for each of the four structural embodiments disclosed hereinabove, the phase separation phenomena can be avoided in an InGaAlN material system by operating at a crystal growth temperature between on the order of 500 °C and around 1000 °C, when the Ga mole fraction, x, and the AlN mole fraction, y, of the all

15 constituent layers of the laser diodes are made to satisfy approximately the relationship of $0 < x + y < 1$, $1 <= x/0.80 + y/0.89$. The result is the substantially uniform distribution of In atoms, Ga atoms, and Al atoms in each constituent layer according to the atomic mole fraction.

Figure 16 shows the content choice line of Ga content, x, and Al content, y,

20 in an InGaAlN system to avoid phase separation phenomenon at growth temperatures below around 1000 °C. The line in Figure 16 shows the exemplary line of $x + 1.2y = 1$. Therefore, by ensuring that the Ga content and Al content of the constituent InGaAlN layers of a laser diode formed on a GaN substrate have a relationship of $x + 1.2y$ nearly equal to 1 and $0 < x + y < 1$, $1 <= x/0.80 + y/0.89$, a

25 laser diode on a GaN substrate with low defect density and no or very little phase separation can be obtained.

In addition, other semiconductor structures can be fabricated with the materials system discussed above. Group-III nitride materials, especially GaN and AlN, are promising for use in electronic devices which can operate under high-power

30 and high-temperature conditions -- for example, microwave power transistors. This results, in part, from their wide band gap (3.5 eV for GaN and 6.2 eV for AlN), high breakdown electronic field, and high saturation velocity. By comparison, the band gaps of AlAs, GaAs, and Si are 2.16 eV, 1.42 eV, and 1.12 eV, respectively. This has led to significant research in the use of AlGaN/GaN materials for such field effect

35 transistors (FETs). However, as noted previously hereinabove, the different lattice constants of AlGaN and GaN cause the generate of significant defects, limiting the mobility of electrons in the resultant structure and the utility of such materials

systems for FET use.

The present invention substantially overcomes these limitations, in that the InGaAlN/GaN material of the present invention has a lattice constant equal to GaN. As discussed hereinabove, a quaternary materials system of $In_{1-x-y}Ga_xAl_yN$, where the

5 GaN mole fraction (x) and AlN mole fraction (y) satisfy the relationships $0 < x + y < 1$, $1 <= x/0.8 + y/0.89$ and $x + 1.2y = 1 \pm 0.1$ not only has a band gap greater than 3.1 eV, but also has a lattice constant substantially equal to GaN. This permits fabrication of semiconductor structures such as FETs which have substantially uniform atomic content distribution in the various layers. Therefore, by using an

10 InGaAlN/GaN material system in accordance with the present invention, whose GaN mole fraction, x and AlN mole fraction, y satisfy the above relationships, high-power and high-temperature transistors with low defect density can be realized.

Referring to Figure 17A, there is shown therein an exemplary embodiment of a heterojunction field effect transistor(HFET) using InGaAlN/GaN material in

15 accordance with the present invention. On a GaN substrate 520, a 0.5 µm i-GaN layer 525 is formed, followed by a thin, approximately 10 nm GaN conducting channel layer 530 and a 10 nm InGaAlN layer 535. Source and drain electrodes 540A-B, and gate electrode 545 are formed in a conventional manner. In the structure, the GaN mole fraction, x, and AlN mole fraction, y, of the InGaAlN layer

20 are set to be 0.64 and 0.3, respectively. In this case, the value of x and y satisfy the relationship of $0 < x + y < 1$, $1 <= x/0.8 + y/0.89$, and $x + 1.2y = 1 \pm 0.1$. This results in an InGaAlN layer substantially without phase separation and with a lattice constant equal to GaN. In turn, this permits high electron velocities to be achieved because the two dimensional electron gas formed in the heterointerface of InGaAlN and GaN

25 layer is not scattered by any fluctuation in atomic content of the InGaAlN layer (such as would be caused in the presence of defects). Moreover, the band gap of the InGaAlN is larger than 4 eV so that reliable high-temperature operation can be achieved by using the structure shown in Figure 17A.

Similarly, Figure 17B shows an embodiment of a heterojunction bipolar

30 transistor(HBT) in accordance with the present invention. On the GaN substrate 550, a 400 nm thick n-type InGaAlN collector layer 555 is formed, followed by a 50 nm thick p-type GaN base layer 560, and a 300 nm thick emitter layer 565. Base electrode 570, collector electrode 575 and emitter electrode 580 are formed conventionally. As with Figure 17A, for the exemplary embodiment of Figure 17B the

35 GaN and AlN mole fractions x and y of the InGaAlN layer are set to be 0.64 and 0.3, respectively, and x and y are required to satisfy the same relationships as discussed above. As with Figure 17A, an InGaAlN layer without significant phase separation

and with a lattice constant equal to GaN is realized, resulting in a very high quality heterojunction of InGaAlN/GaN. In addition, the band gap of the InGaAlN emitter layer (4.2 eV) is larger than that of GaN base layer (3.5eV) so that holes generated in the p-type base layer are well confined in that base layer. This results because

5 of the larger valence band discontinuity between GaN and InGaAlN than would occur in a GaN homojunction bipolar transistor. This has the benefit of obtaining a large current amplification of collector current relative to base current. Moreover, as mentioned above, the bandgap of the InGaAlN and the GaN layer is large so that the transistor can be used reliably in high-temperature applications.

10   Referring next to Figure 18, there is shown therein an implementation of the present invention as a phototransistor. In this regard, GaN and AlGaN are attractive materials for photo detectors in ultraviolet(UV) range, since both GaN and AlN have a wide band gap (3.5 eV for GaN which corresponds to the light wavelength of 200 nm, 6.2 eV for AlN which corresponds to the light wavelenght of 350 nm). Due to the

15 direct band gap and the availability of AlGaN in the entire AlN alloy composition range, AlGaN/GaN based UV photo detectors have the advantage of high quantum efficiency, as well as tunability of high cut-off wavelength. However, the lattice constant of AlGaN is sufficiently different from GaN that defects tend to be formed, which leads increased leakage current.

20        $In_{1-x-y}Ga_xAl_yN$ quaternary material whose GaN mole fraction, x and AlN mole fraction, y satisfy the relationship of $0 < x + y < 1$, $1 <= x/0.8 + y/0.89$, offers not only a band gap larger than 3.1 eV, but also can be fabricated in layers with equal atomic content distribution, so that InGaAlN material also can be used for UV photo detector applications. Moreover, the $In_{1-x-y}Ga_xAl_yN$ quaternary material whose GaN mole

25 fraction, x and AlN mole fraction, y satisfy the relationship of $x + 1.2y = 1$ has a lattice constant equal to GaN. Therefore, by using InGaAlN/GaN material whose GaN mole fraction, x and AlN mole fraction, y satisfy the above relationship, UV photo detectors with low defect density can be realized. In the event that detection of other frequencies is desired, for example blue light, only slight modification is required.

30   As shown in Figure 18, the semiconductor device of the present invention can be implemented as a heterojunction phototransistor(HPT) using InGaAlN/GaN material. On the GaN substrate 700, an InGaAlN collector layer 705 is formed on the order of 500 nm thick n-type, followed by the formation of a 200 nm thick p-type GaN base layer 710. Thereafter, an emitter layer 715 on the order of 500 nm thick

35 is formed. On the emitter layer, a ring shaped electrode 720 is formed to permit light to impinge on the base layer.

        In an exemplary structure, the GaN mole fraction, x and AlN mole fraction, y

of the InGaAlN layer are set to be 0.64 and 0.3, respectively. In this case, the value of x and y satisfy the relationship of $0 < x + y < 1$, $1 <= x/0.8 + y/0.89$, and $x + 1.2y = 1$, so that an InGaAlN layer can be formed with substantially avoids phase separation while having a lattice constant equal to GaN, thus permitting the formation of a high

5   quality heterojunction of InGaAlN/GaN. The band gap of the InGaAlN emitter layer (4.2 eV which corresponds to the light wavelength of 290 nm) is larger than that of GaN base layer (3.5eV which corresponds to the light wavelength of 350 nm). The light impinges on the emitter side. For the embodiment shown, impinging light in the wavelength range between 290 nm and 350 nm is transparent to the emitter layer,

10   so that the light in that range is absorbed in the GaN base layer and generates electron and hole pairs. The holes generated by the optical absorption in the p-type base layer are well confined in the base layer because the valence band discontinuity between GaN and InGaAlN is larger than that for a conventional GaN homojunction photo transistor. This leads to the induction of a larger emitter current,

15   which offers better electronic neutralization in the base region than in the case of the homojunction photo transistor. Therefore, UV photo detectors with high quantum efficiency and high sensitivity, and the resultant high conversion efficiency from input light to collector current, are obtained. In the event that other frequencies are to be detected, the GaN base layer may be replaced with, for example for blue light,

20   InGaN.

In addition to the phototransistor embodiment of Figure 18, it is also possible to implement a photodiode in accordance with the present invention. Referring to Figure 19, an n-type substrate 900 is provided, on which is formed an n-type GaN first cladding layer 905. Above the cladding layer is formed an n-type layer 910 of

25   $In_{1-x-y}Ga_xAl_yN$ quaternary material or equivalent, which conforms to the relationships discussed above in connection with Figure 18. An active layer 915 is thereafter formed, and above that is formed a layer 920 of p-type $In_{1-x-y}Ga_xAl_yN$ quaternary material. Then, a p-type second cladding layer 925 is formed above the layer 920, and a window 930 is formed therein to expose a portion of the layer 920. The

30   window 930 provides a port by which light can impinge on the layer 920, causing the creation of holes. A pair of electrodes 935 and 940 may be fabricated in a conventional manner, with the electrode 935 typically being a ring electrode around the window 930. It will be appreciated that the band gap of the second cladding layer 925 is preferably larger than the band gap of the layer 920, which is in turn preferably

35   larger than the band gap of the active layer 915; such an approach provides sensitivity to the widest range of wavelengths of light. If the event a narrower range is desired, a material with a lower band gap than the layer 920 may be used for the

layer 925. In addition, it is also not necessary to include the layer 925 in all embodiments, as the layers 910, 915 and 920 provide, in at least some instances, an adequate photosensitive pn-junction.

Having fully described a preferred embodiment of the invention and various
5 alternatives, those skilled in the art will recognize, given the teachings herein, that numerous alternatives and equivalents exist which do not depart from the invention. It is therefore intended that the invention not be limited by the foregoing description, but only by the appended claims.

We claim:

1.   A semiconductor structure comprising:

5   a first cladding layer of InGaAlN material having a first conduction type,

an InGaAlN active layer, and

a second cladding layer of InGaAlN material having a conduction type opposite the first conduction type, the mole fractions of the constituent elements of each layer being selected to minimize phase separation.

10

2.   A semiconductor structure comprising:

a first cladding layer of InGaAlN material having a first conduction type,

an InGaAlN active layer, and

a second cladding layer of InGaAlN material having a conduction type

15 opposite the first conduction type, the crystal growth temperature and the mole fractions of the constituent elements of each layer being selected to minimize phase separation.

3.   A light emitting device according to claim 1, wherein the GaN mole fraction,

20 x, and the AlN, y, of all the constituent layers satisfy the condition that x + 1.2y nearly equals to a constant value.

4.   A light emitting device according to claim 1, wherein the GaN mole fraction,

x, and the AlN, y, of all the constituent layers satisfy the condition that x + 1.2y nearly

25 equals to 1.

5.   A light emitting device comprising:

a first conduction type of an InGaAlN first cladding layer without phase separation, an InGaAlN active layer without phase separation, and a second

30 conduction type of InGaAlN second cladding layer without phase separation, said InGaAlN second cladding layer having a ridge structure, all successively formed one upon each other.

6.   A light emitting device according to claim 4, wherein the GaN mole fraction,

35 x, and the AlN, y, of all the constituent layers satisfy the condition that x + 1.2y nearly equals constant value.

7.   A light emitting device according to claim 4, wherein the GaN mole fraction, x, and the AlN, y, of all the constituent layers satisfy the condition that $x + 1.2y$ nearly equals 1.

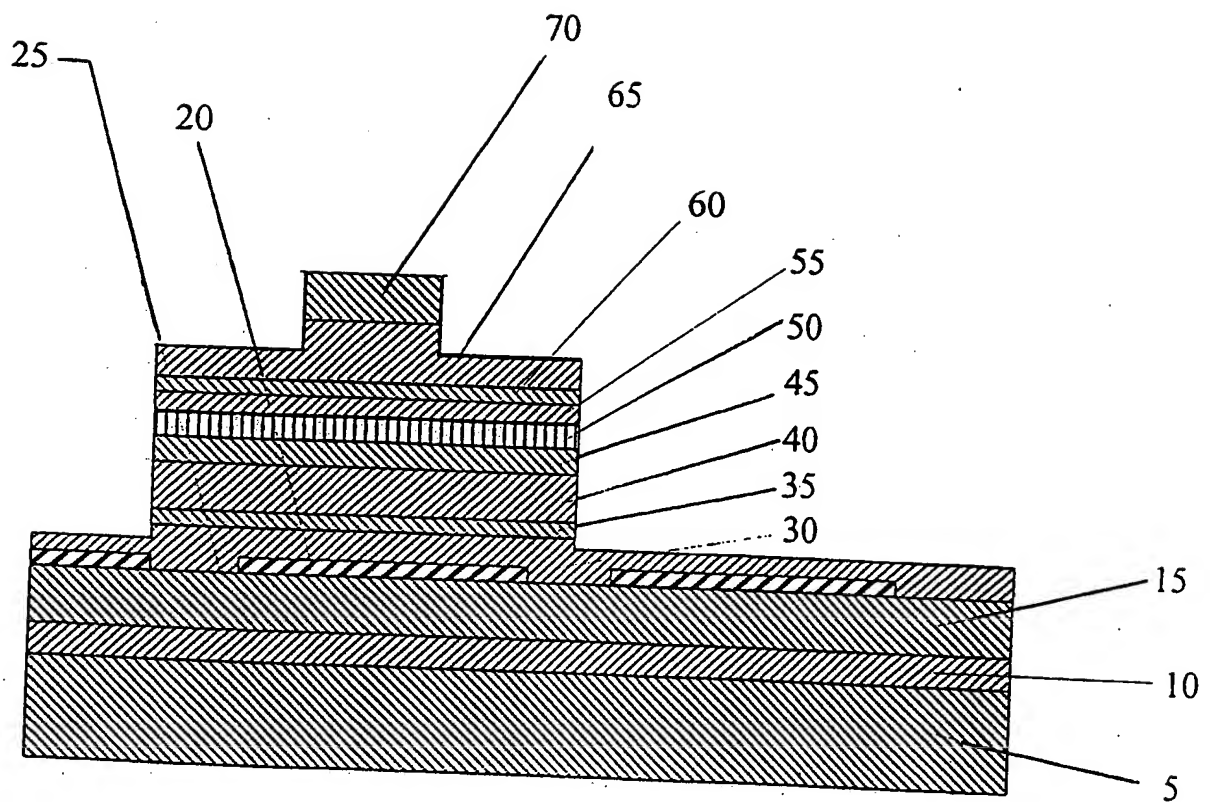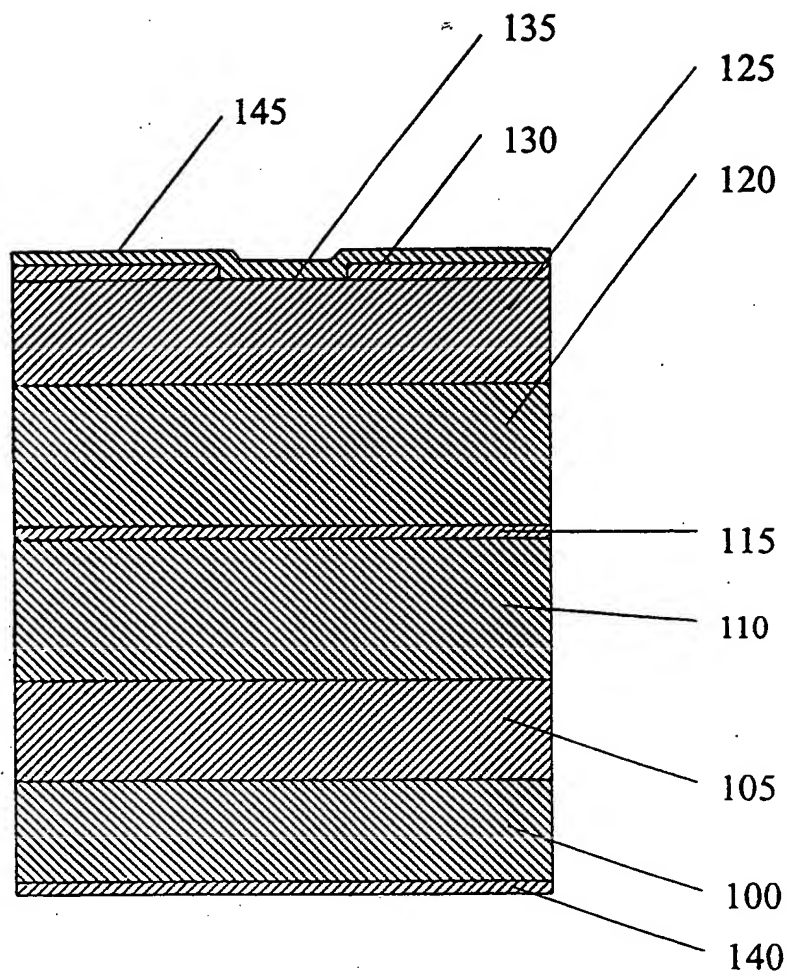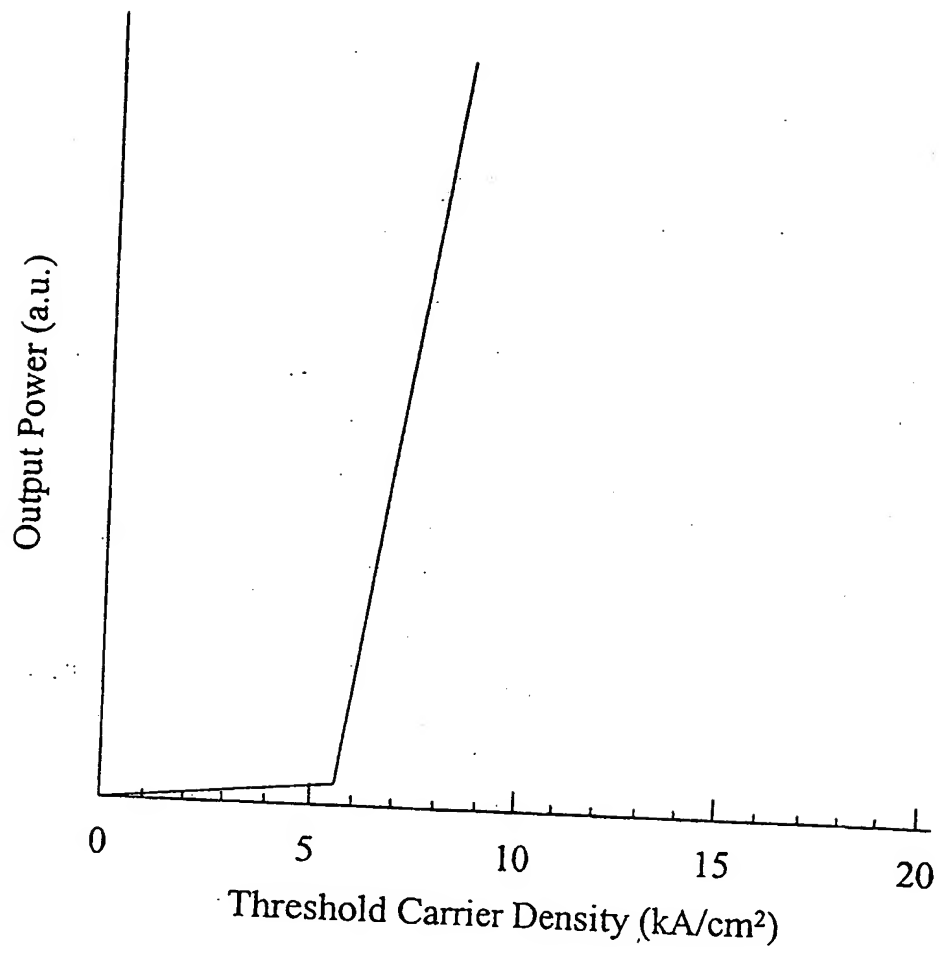5 8.   A light emitting device comprising:

a certain conduction type of a GaN first cladding layer, an $In_{1-x1-y1}Ga_{x1}Al_{y1}N$ second cladding layer of said certain conduction type, an $In_{1-x2-y2}Ga_{x2}Al_{y2}N$ active layer, an opposite conduction type of an $In_{1-x1-y1}Ga_{x1}Al_{y1}N$ third cladding layer, an opposite conduction type of GaN fourth cladding layer, all successively formed one upon each other, wherein x1, x2 define the gallium mole fraction, y1 and y2 define the aluminum mole fraction, and x1, y1, x2, and y2 have a relationship of $0 < x1 + y1 < 1$, $0 < x2 + y2 < 1$, $1 <= x1/0.80 + y1/0.89$, $1 <= x2/0.80 + y2/0.89$, and $Eg_{InN}(1-x1-y1) + Eg_{GaN}x1 + Eg_{AlN}y1 > Eg_{InN}(1-x2-y2) + Eg_{GaN}x2 + Eg_{AlN}y2$, where Eg_{InN}, Eg_{GaN}, and Eg_{AlN} are the bandgap energy of InN, GaN, and AlN, respectively.

15

9. A light emitting device according to claim 7, wherein said active layer is an InGaAlN single or multiple quantum well active layer whose GaN mole fraction, xw, and AlN mole fraction, yw of all the constituent layers of said active layer satisfy the relationship of $0 < xw + yw < 1$ and $1 <= x/0.80 + y/0.89$.

20

10. A light emitting device according to claim 7, wherein the condition of $xs + 1.2ys$ nearly equals to a constant value is satisfied, wherein xs and ys are the GaN mole fraction and the AlN mole fraction, respectively in each constituent InGaAlN layers.

25 11. A light emitting device according to claim 7, wherein the relationship of $xs + 1.2ys$ nearly equals 1 is satisfied, where xs and ys are the GaN mole fraction and the AlN mole fraction, respectively in each constituent InGaAlN layers.

12. A light emitting device comprising:

30   a certain conduction type of an $In_{1-x1-y1}Ga_{x1}Al_{y1}N$ first cladding layer of said certain conduction type, an $In_{1-x2-y2}Ga_{x2}Al_{y2}N$ active layer, an opposite conduction type of an $In_{1-x3-y3}Ga_{x3}Al_{y3}N$ second cladding layer, said $In_{1-x3-y3}Ga_{x3}Al_{y3}N$ second cladding layer has a ridge strict, all successively formed one upon each other, wherein x1, x2, and x3 define the gallium mole fraction, y1, y2, and y3 define the aluminum mole fraction, and x1, y1, x2, y2, x3, and y3 have a relationship of $0 < x1 + y1 < 1$, $0 < x2 + y2 < 1$, $0 < x3 + y3 < 1$, $1 <= x1/0.80 + y1/0.89$, $1 <= x2/0.80 + y2/0.89$, $1 <= x3/0.80 + y3/0.89$, $Eg_{InN}(1-x1-y1) + Eg_{GaN}x1 + Eg_{AlN}y1 > Eg_{InN}(1-x2-y2) + Eg_{GaN}x2 + Eg_{AlN}y2$,

and $Eg_{InN}(1-x3-y3) + Eg_{GaN}x3 + Eg_{AlN}y3 > Eg_{InN}(1-x2-y2) + Eg_{GaN}x2 + Eg_{AlN}y2$, where Eg_{InN}, Eg_{GaN}, and Eg_{AlN} are the bandgap energy of InN, GaN, and AlN, respectively.

13. A light emitting device according to claim 11, wherein said active layer is an
5 InGaAlN single or multiple quantum well active layer whose GaN mole fraction, xw, and AlN mole fraction, yw of all the constituent layers satisfy the relationship of $0 < xw + yw < 1$ and $1 <= x/0.80 + y/0.89$.

14. A light emitting device according to claim 11, wherein the condition of $xs + 1.2ys$
10 nearly equals to a constant value is satisfied, where xs and ys are the GaN mole fraction and the AlN mole fraction, respectively in each constituent InGaAlN layers.

15. A light emitting device according to claim 11, wherein the relationship of $xs + 1.2ys$ nearly equals 1 is satisfied, wherein xs and ys are the GaN mole fraction and
15 the AlN mole fraction, respectively in each constituent InGaAlN layers.

16.   A photo detector device comprising:
     a certain conduction type of an InGaAlN collector layer without phase separation, a opposite conduction type of InGaAlN base layer without phase separation, a
20 conduction type of said certain conduction type of InGaAlN emitter layer without phase separation, all successively formed one upon each other, wherein the bandgap of said InGaAlN base layer is smaller than the other InGaAlN layers.

17.   A photo detector device according to claim 16, wherein the GaN mole fraction,
25 x, and the AlN, y, of the said constituent InGaAlN layers satisfy the relationship of $0 < x + y < 1$, $1 <= x1/0.80 + y1/0.89$.

18.   A photo detector device according to claim 17, wherein the GaN mole fraction, x, and the AlN, y, of all the constituent layers satisfy the condition that $x + 1.2y$ nearly
30 equals to a constant value.

19.   A photo detector device according to claim 17, wherein the GaN mole fraction, x, and the AlN, y, of all the constituent layers satisfy the condition that $x + 1.2y$ nearly equals to 1.
35

Figure 1 --
PRIOR ART

Figure 2

Figure 3

125
120
115 — Figure 4A
110
105
100

130
125
120
115
110 — Figure 4B
105
100

130 — 135 — 130
125
120
115
110 — Figure 4C
105
100

130 — 135 — 145 — 130
125
120
115
110 — Figure 4D
105
100
140

145
135
125
130

500

120
115
110
105
100
140
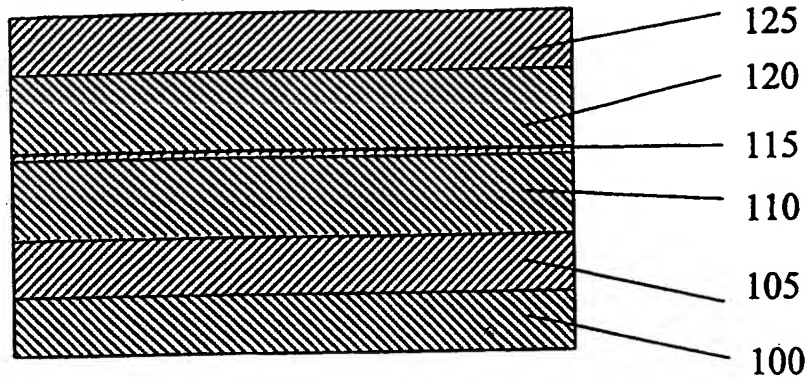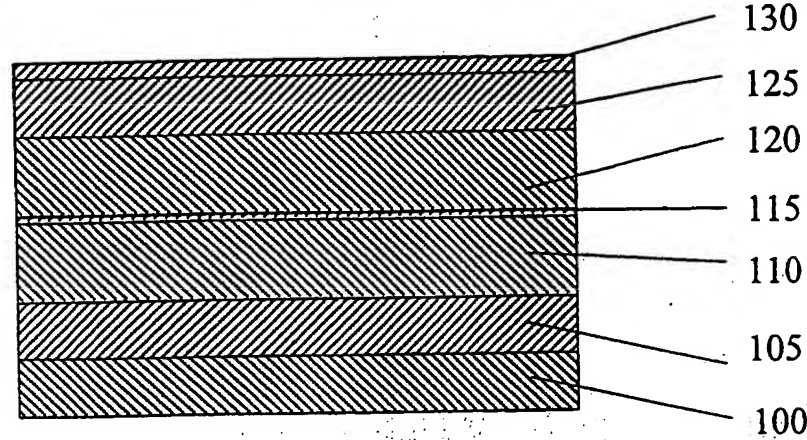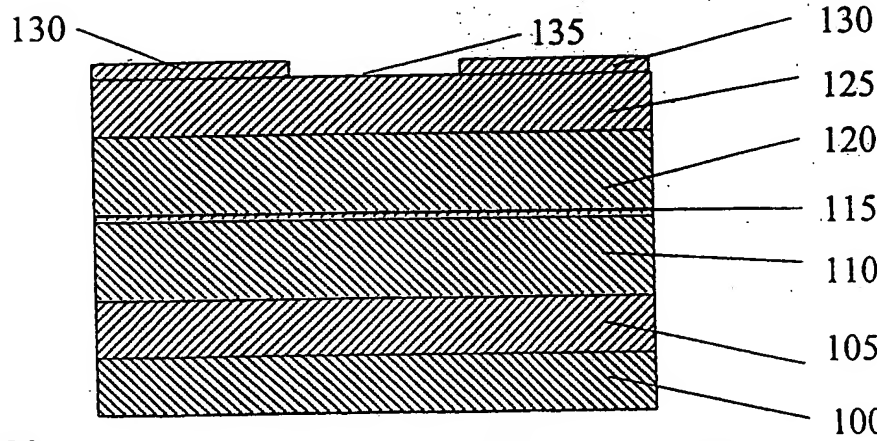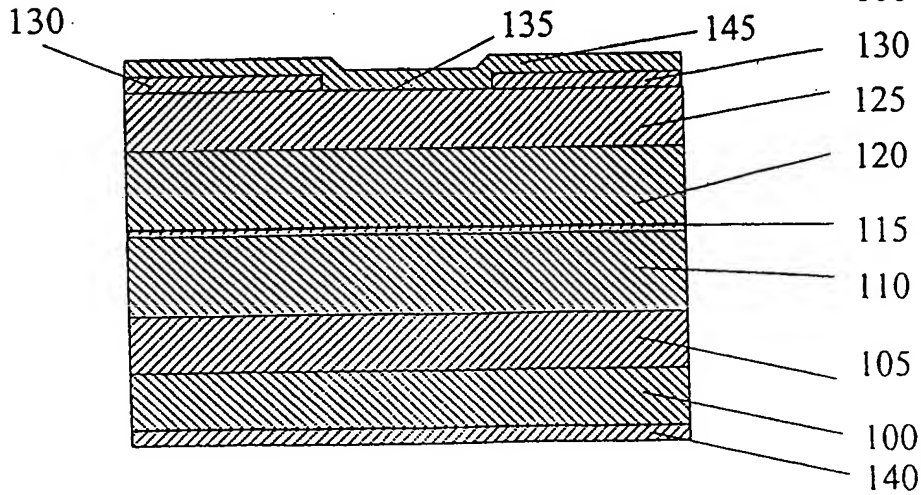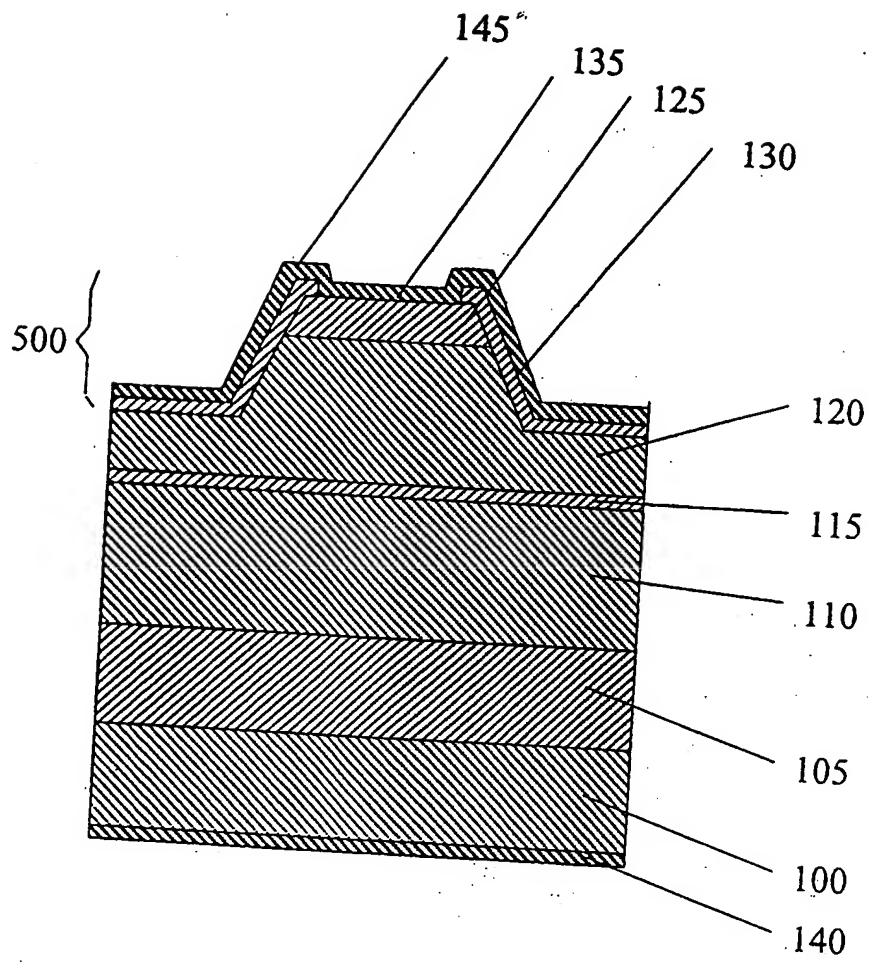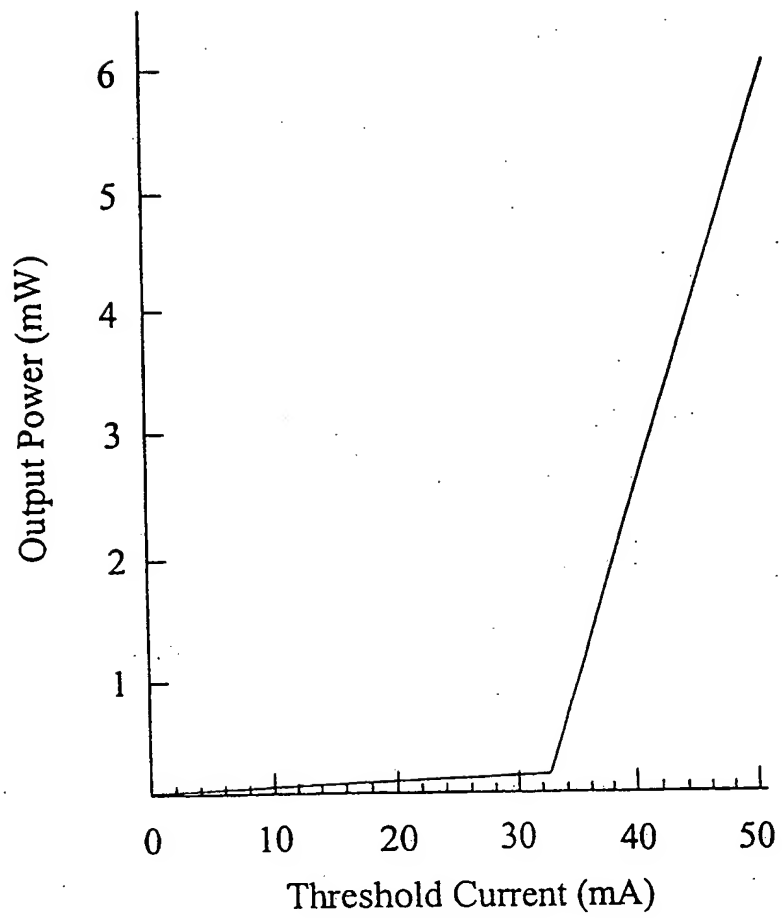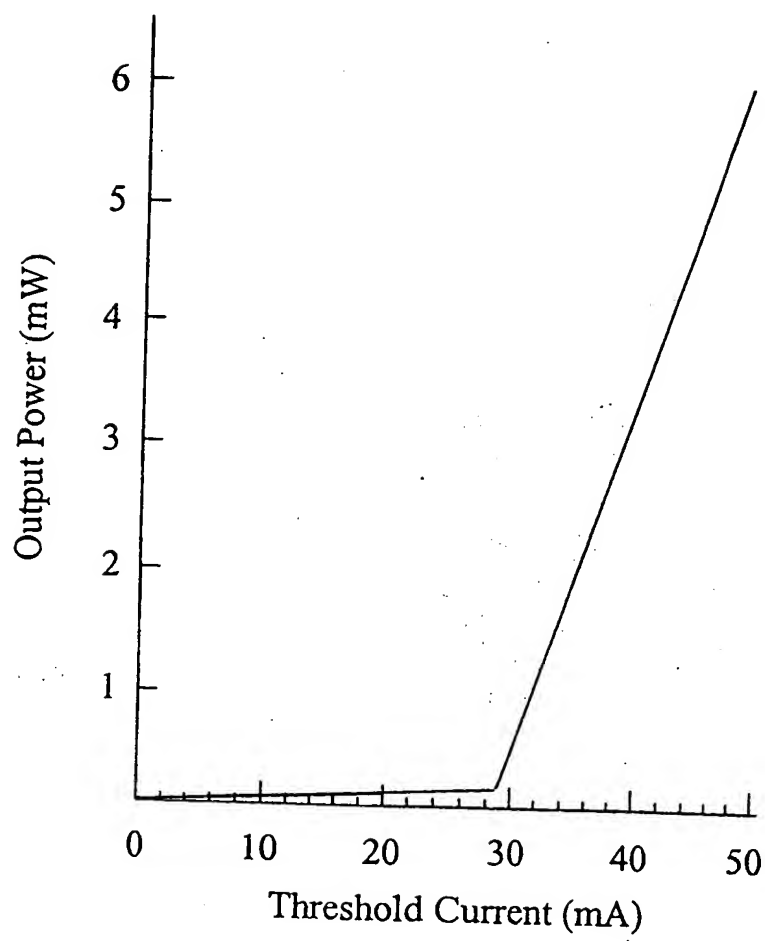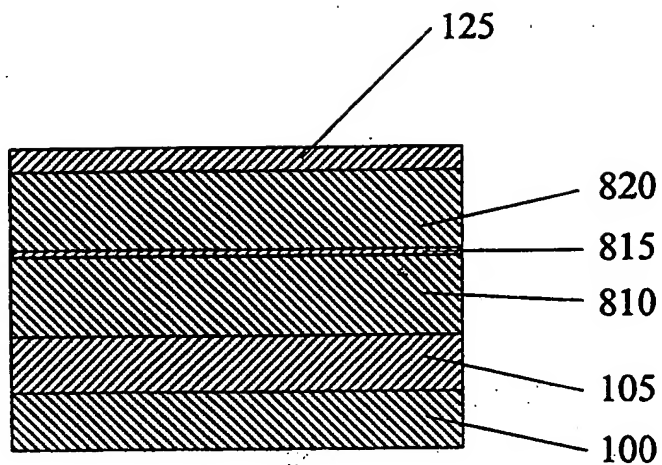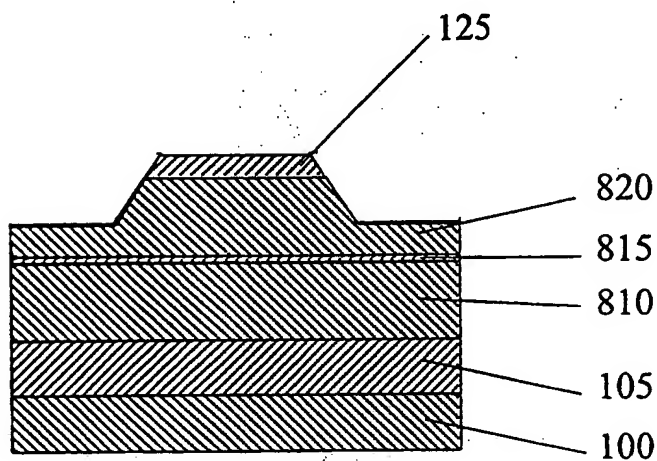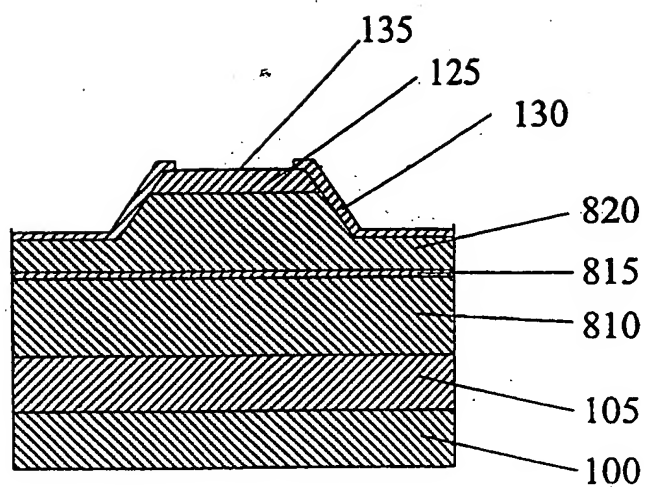
Figure 5

Figure 6

Figure 7A
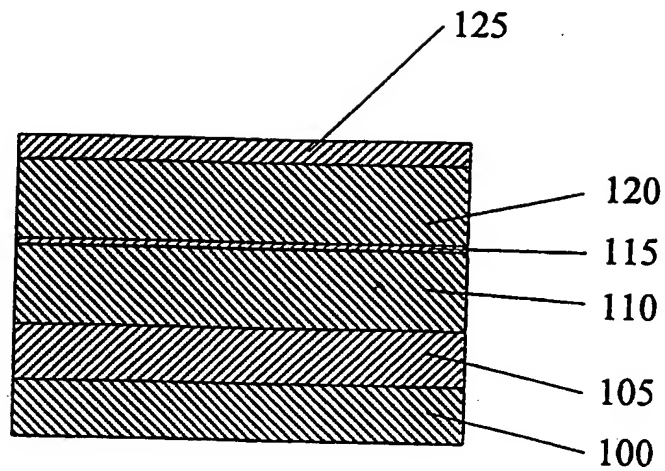
Figure 7B
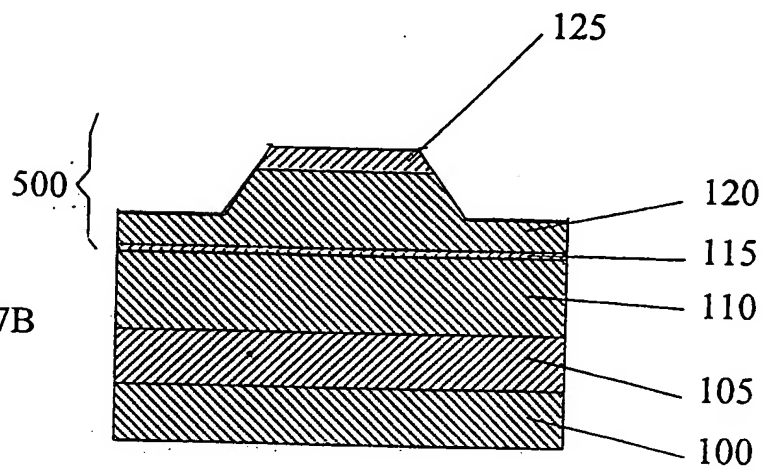
Figure 7C
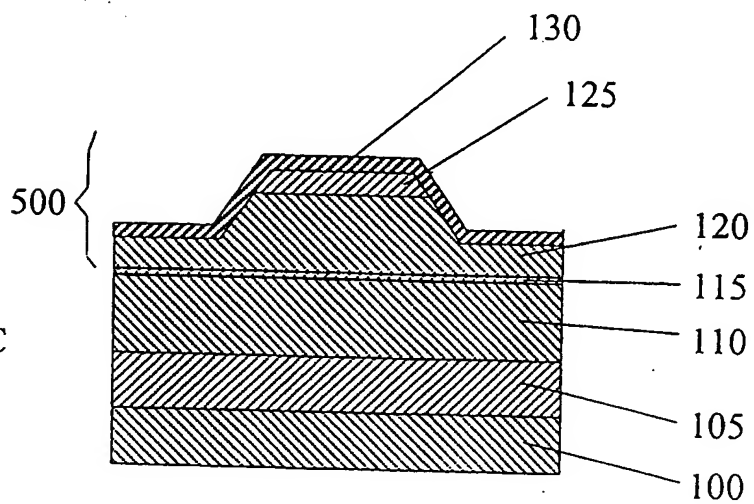
Figure 7D
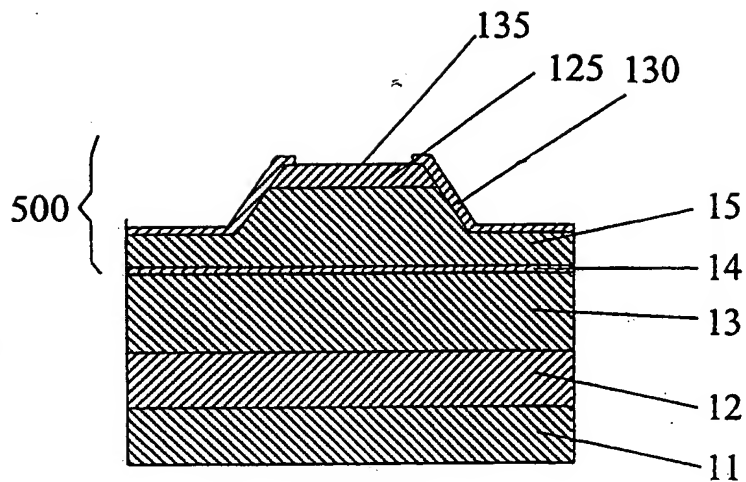
Figure 7E
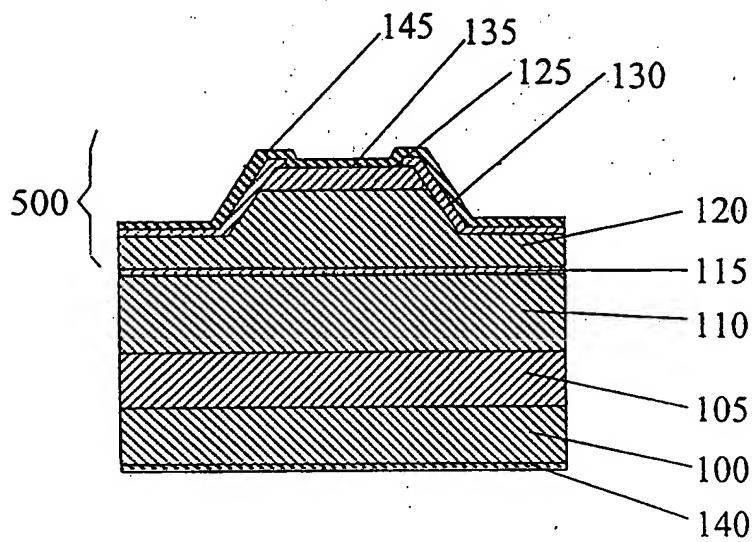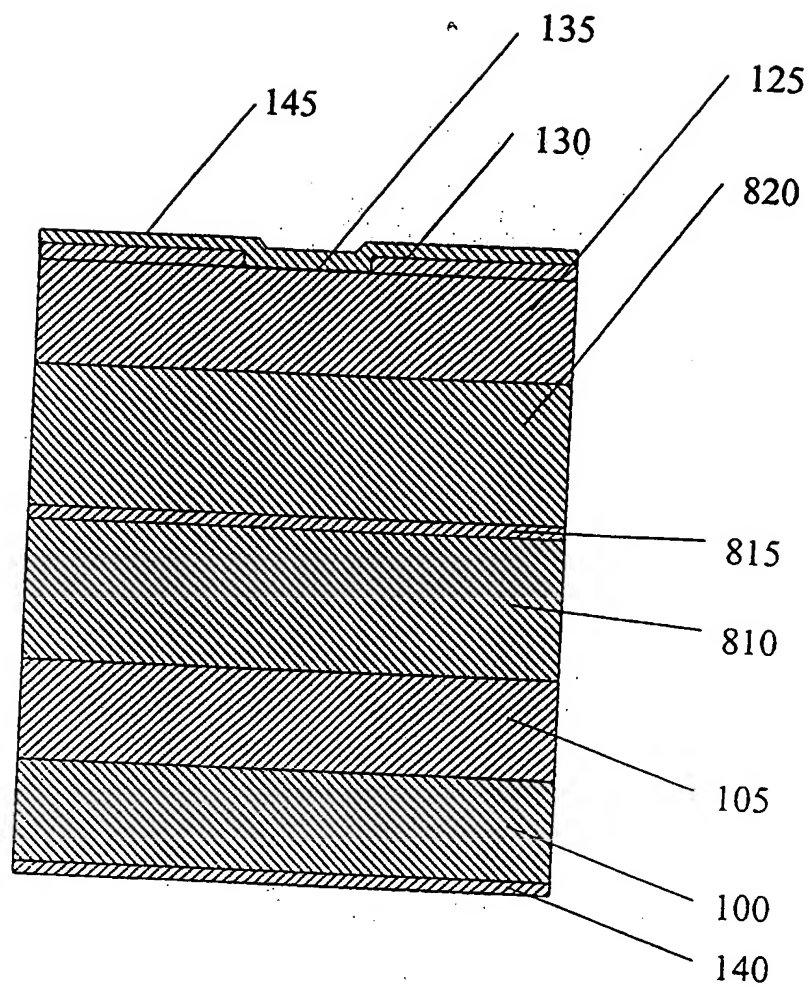
Figure 8

Figure 9

Figure 10A

825
820
815
810
105
100

Figure 10B

830
825
820
815
810
105
100

Figure 10C

130
135
130
125
820
815
810
105
100

Figure 10D

135
145
130
130
125
820
815
810
105
100
140
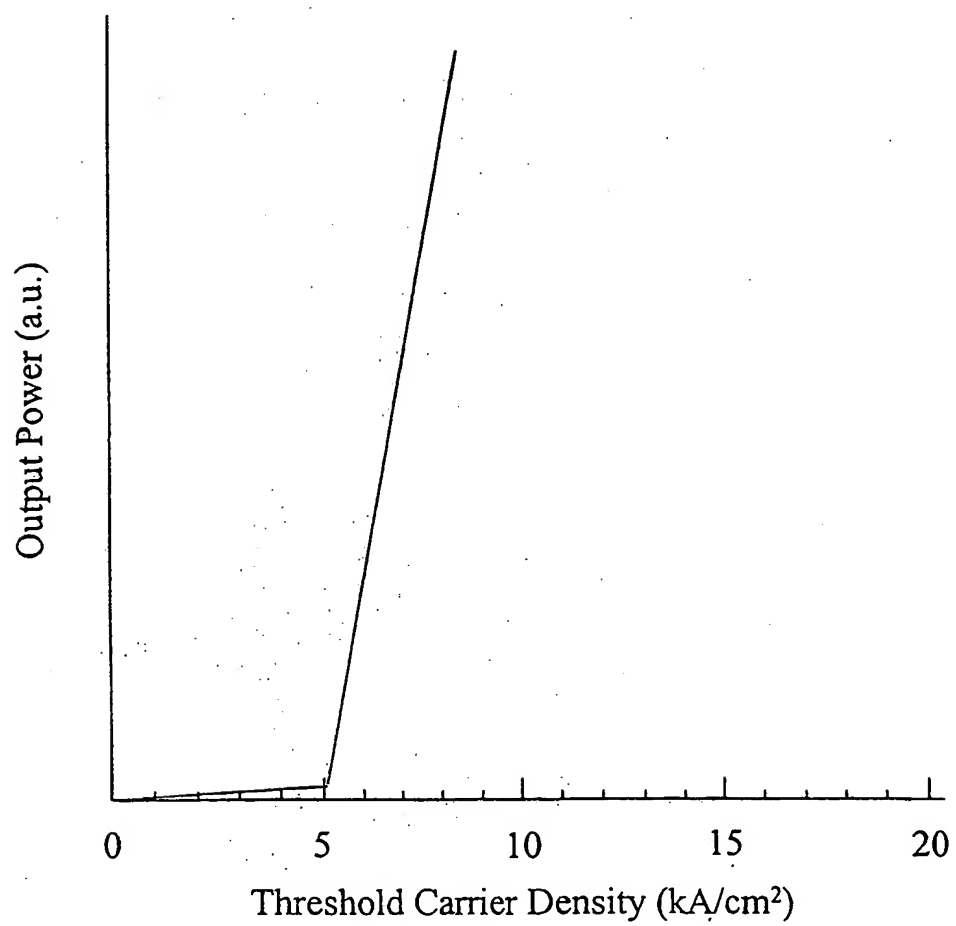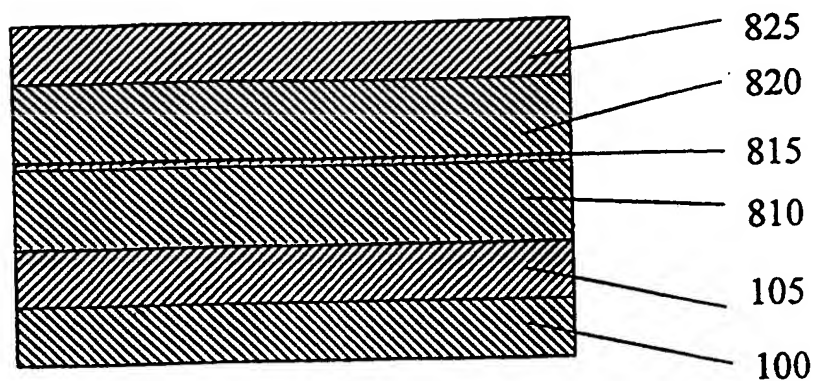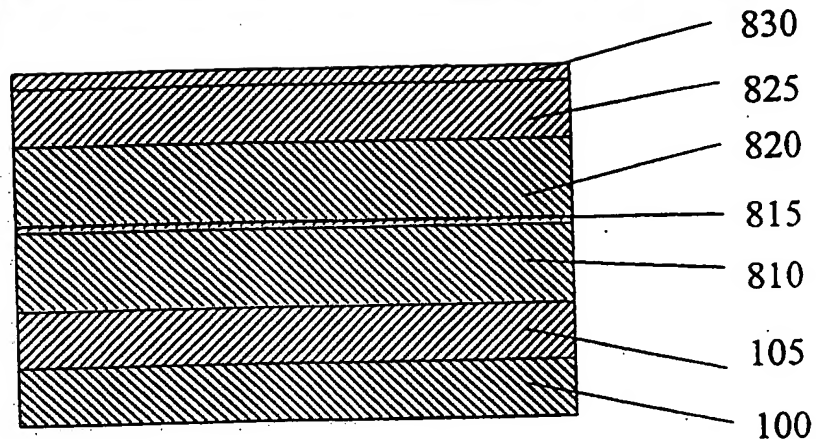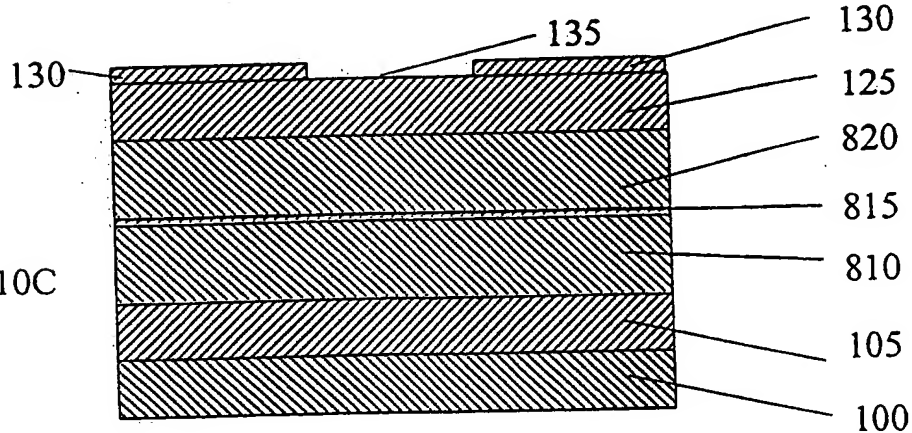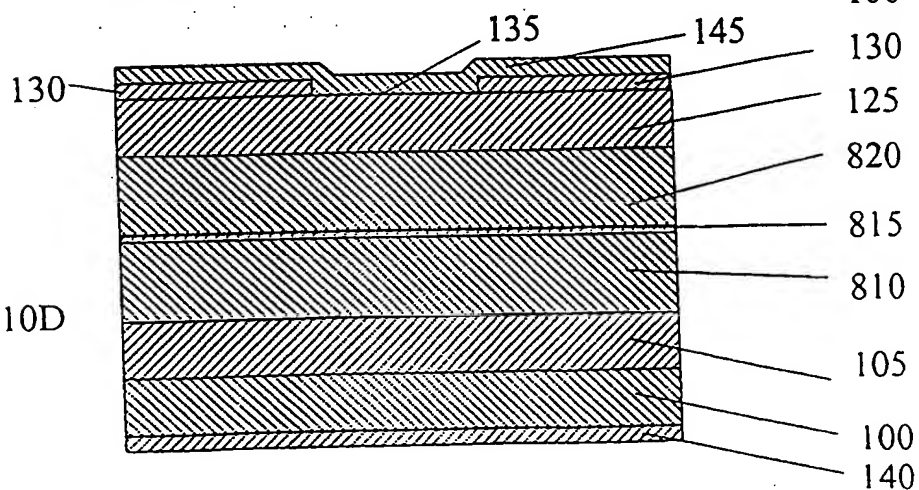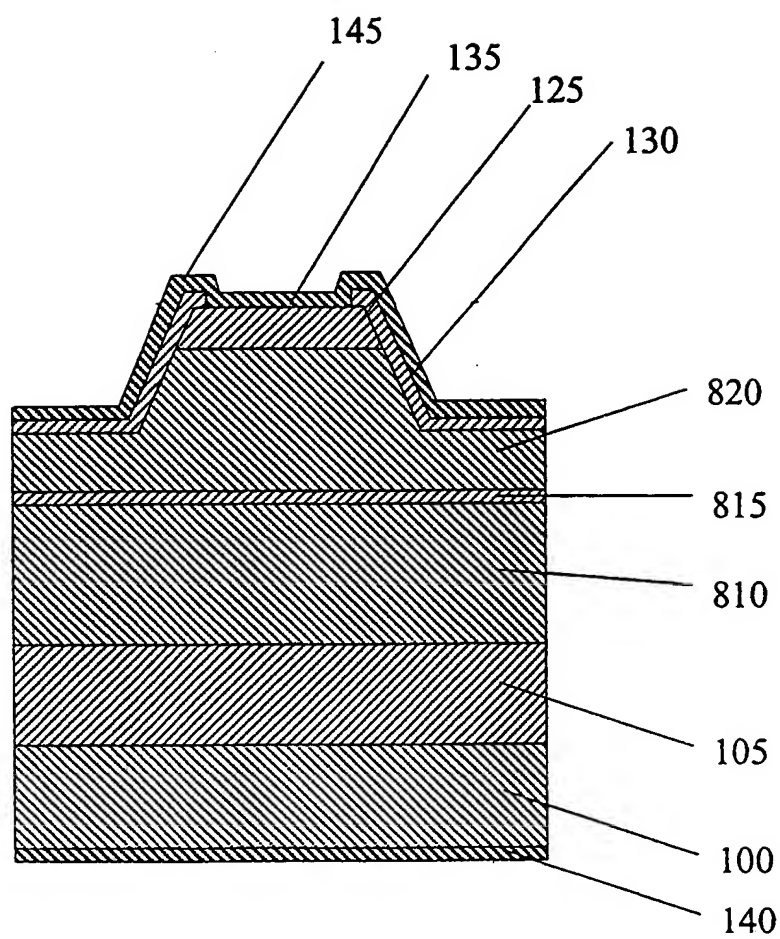
Figure 11

Figure 12

Figure 13A

125
820
815
810
105
100

Figure 13B

125
820
815
810
105
100

Figure 13C

130
125
820
815
810
105
100
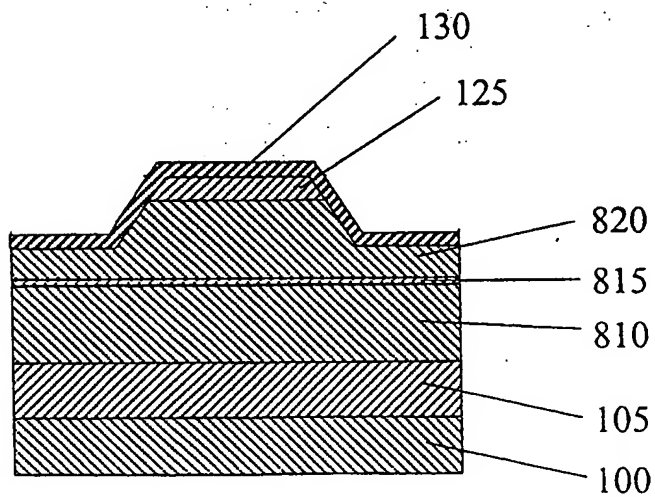
Figure 13D
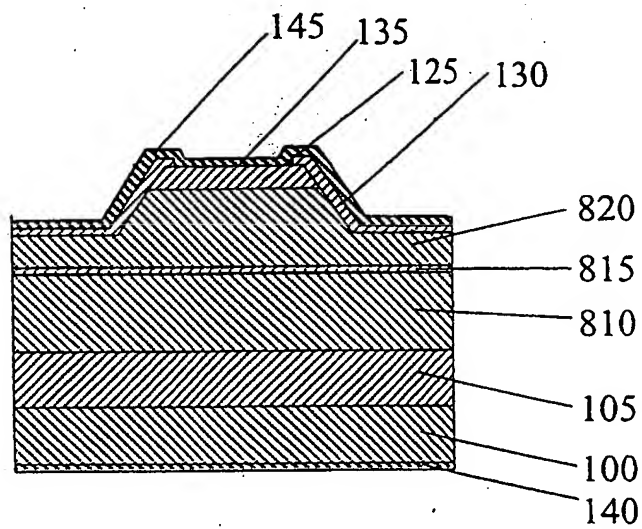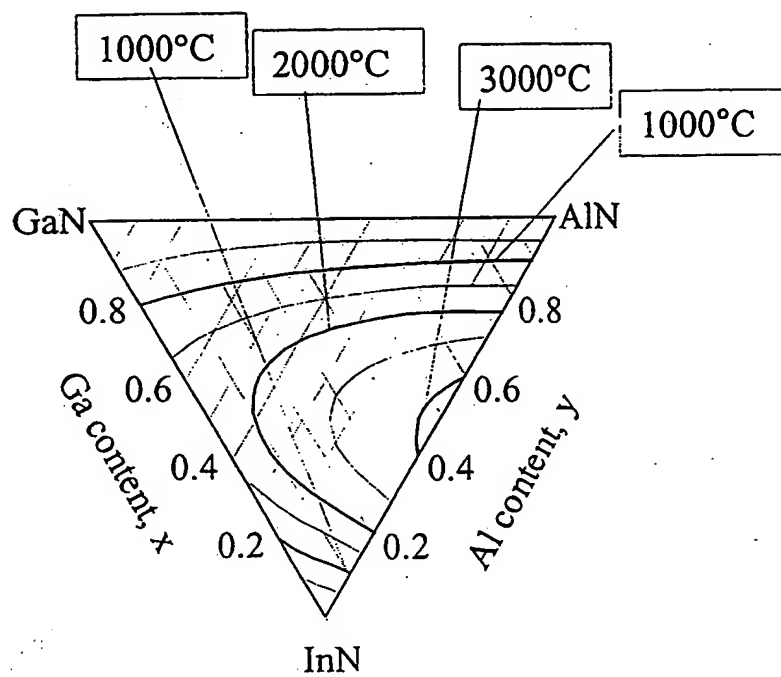
Figure 13E

Figure 14
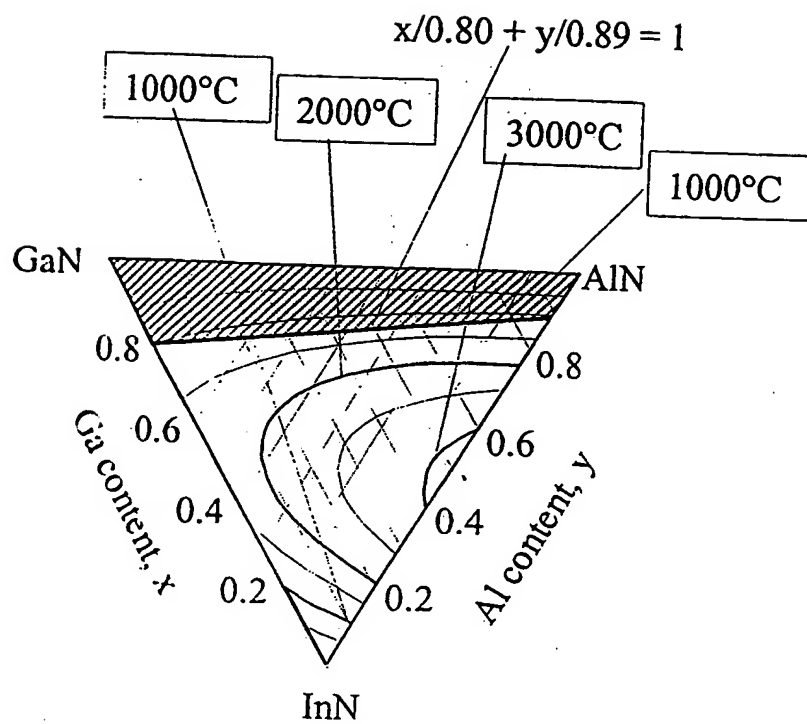
Figure 15

Figure 16

(y) $X = 0.08 - 0.11$

$In_x Al_{1-x} N$

(y) $X = 0 - 0.3$

dème $x = 0.11 - 0.3$

540A Source   545 Gate   540B Drain

535 n-In$_{0.06}$Ga$_{0.64}$Al$_{0.3}$N

530 n-GaN channel layer

525 i-GaN

520 GaN Sub.
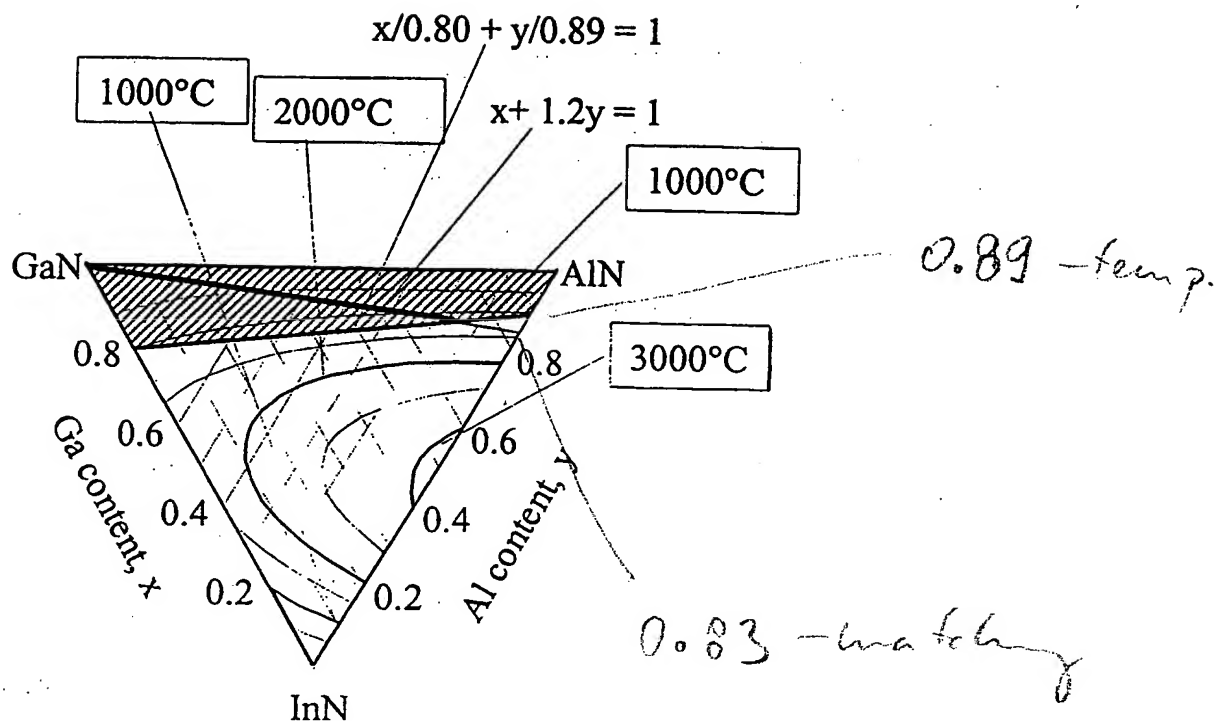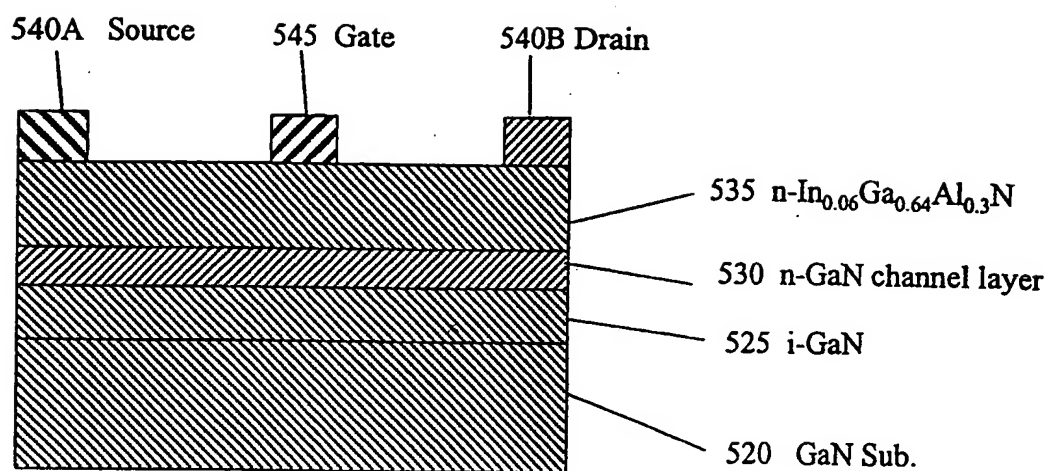
Figure 17A:Heterojunction Field Effect Transistor

565 n-In$_{0.06}$Ga$_{0.64}$Al$_{0.3}$N emitter

560 p-GaN base

580 electrode

570 electrode

575 electrode

555
n-In$_{0.06}$Ga$_{0.64}$Al$_{0.3}$N
collector

550 GaN Sub.
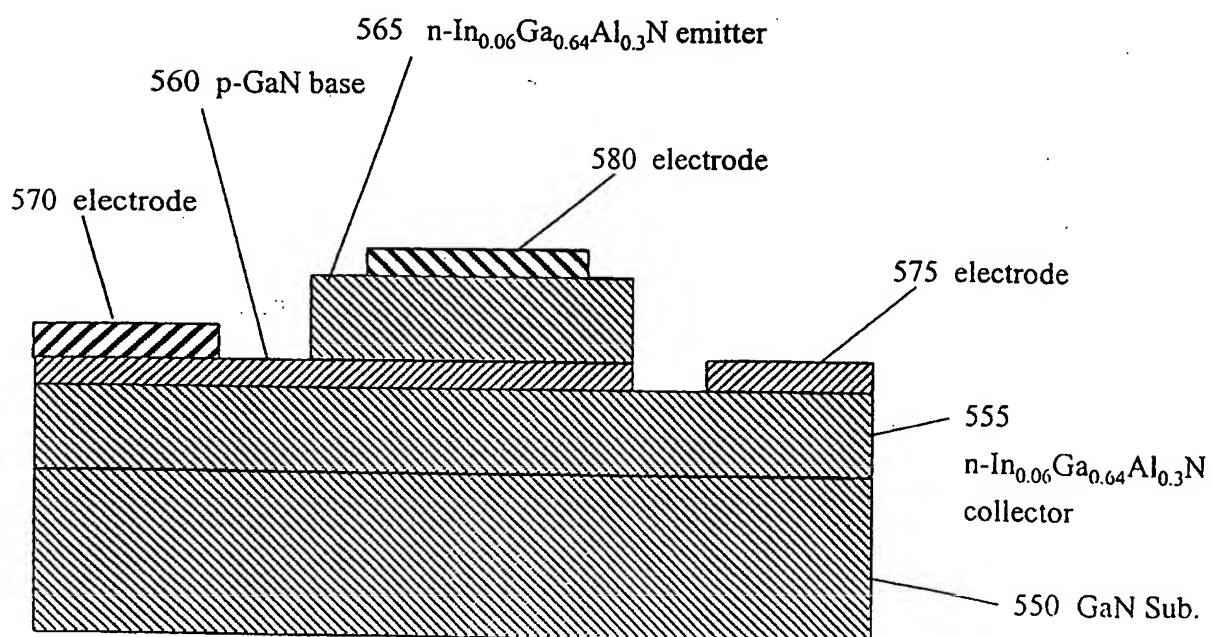
Figure 17B:Heterojunction Bipolar Transistor

715 n-$In_{0.06}Ga_{0.64}Al_{0.3}N$ emitter

710 p-GaN base

720 Ring shaped electrode

725 electrode

705 n-$In_{0.06}Ga_{0.64}Al_{0.3}N$ collector

700 GaN Sub.
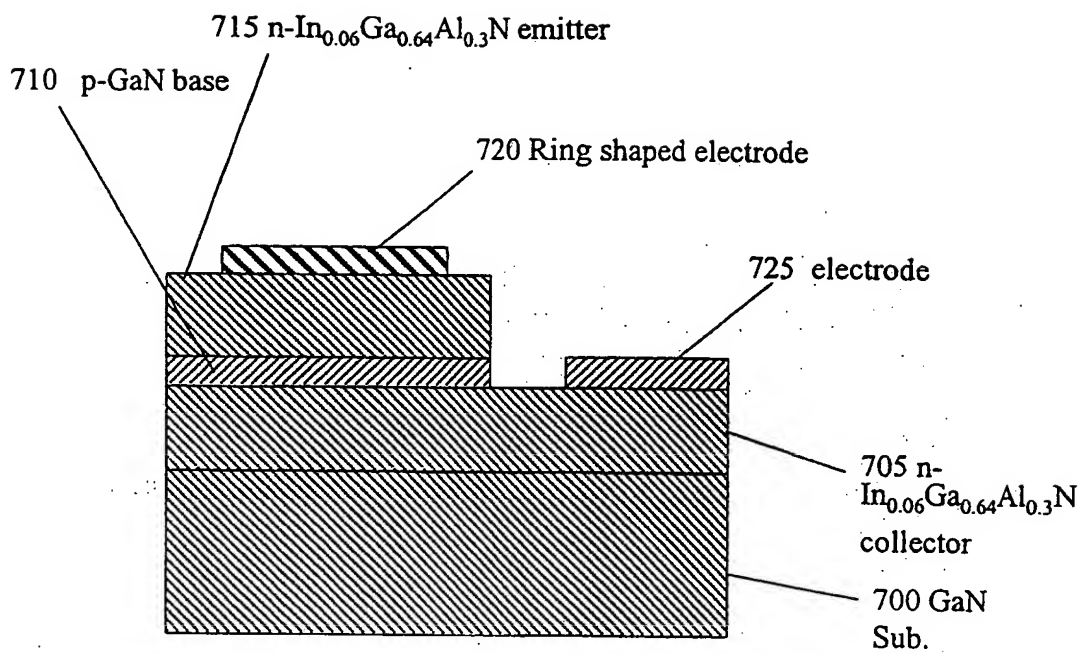
Figure 18 Heterojunction Photo Transistor
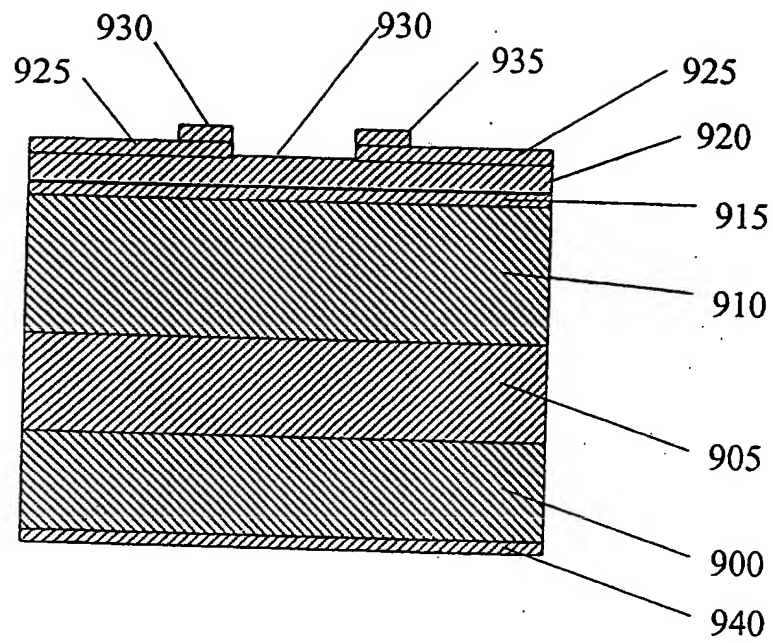
Figure 19

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

Arboleda Drive, Los Altos, CA 94024 (US). HARRIS, James, S., Jr.; 763 Esplanada Way, Stanford, CA 94305 (US).

(54) Title: SEMICONDUCTORS STRUCTURES USING A GROUP III-NITRIDE QUATERNARY MATERIAL SYSTEM WITH REDUCED PHASE SEPARATION AND METHOD OF FABRICATION

(57) Abstract: A group III-nitride quaternary material system and method is disclosed for use in semiconductor structures, including laser diodes, transistors, and photodetectors, which reduces or eliminates phase separation and provides increased emission efficiency. In an exemplary embodiment the semiconductor structure includes a first InGaAlN layer of a first conduction type formed substantially without phase separation, an InGaAlN active layer substantially without phase separation, and a third InGaAlN layer of an opposite conduction type formed substantially without phase separation.

INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7   H01S5/323   H01L33/00   H01L31/0304

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7   H01S   H01L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, PAJ, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category°	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5 828 684 A (VAN DE WALLE CHRISTIAN GILBERT) 27 October 1998 (1998-10-27)	1,3,4,6, 7
Y	the whole document	2

Y	PINER E L ET AL: "Growth and properties of InGaN and AlInGaN thin films on (0001) sapphire" MRS INTERNET JOURNAL OF NITRIDE SEMICONDUCTOR RESEARCH, 1996, MATER. RES. SOC, UK, vol. 1, no. 43, XP002149863 ISSN: 1092-5783	2
A	the whole document	1,5,8, 12,16

A	EP 0 742 622 A (MITSUBISHI CABLE IND LTD) 13 November 1996 (1996-11-13) figure 3	5

	-/--	

[X] Further documents are listed in the continuation of box C.   [X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
12 October 2000	31/10/2000

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Hervé, D

Form PCT/ISA/210 (second sheet) (July 1992)

page 1 of 2

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
A	MATSUOKA T: "Phase separation in wurtzite In/sub 1-x-y/Ga/sub x/Al/sub y/N" MRS INTERNET JOURNAL OF NITRIDE SEMICONDUCTOR RESEARCH, 1998, MATER. RES. SOC, USA, vol. 3, no. 54, XP002149866 ISSN: 1092-5783 the whole document	1,5,8, 12,16
A	MCINTOSH F G ET AL: "GROWTH AND CHARACTERIZATION OF ALLNGAN QUATERNARY ALLOYS" APPLIED PHYSICS LETTERS,US,AMERICAN INSTITUTE OF PHYSICS. NEW YORK, vol. 68, no. 1, 1996, pages 40-42, XP000548792 ISSN: 0003-6951 page 40, column 2, paragraph 2	1,5,8, 12,16
A	US 5 798 537 A (NITTA KOICHI) 25 August 1998 (1998-08-25) column 3, line 55 -column 4, line 44	1,5,8, 12,16
A	US 5 834 331 A (RAZEGHI MANIJEH) 10 November 1998 (1998-11-10) column 2, line 23 - line 45	16
A	US 5 831 277 A (RAZEGHI MANIJEH) 3 November 1998 (1998-11-03) column 1, line 58 -column 2, line 27	16

1

INTERNATIONAL SEARCH REPORT

...formation on patent family members

Patent document cited in search report		Publication date	Patent family member(s)		Publication date
US 5828684	A	27-10-1998	NONE		
EP 0742622	A	13-11-1996	JP	8330678 A	13-12-1996
US 5798537	A	25-08-1998	JP	9129927 A	16-05-1997
US 5834331	A	10-11-1998	NONE		
US 5831277	A	03-11-1998	WO	9842024 A	24-09-1998